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DEPARTMENT OF COMMERCE
U. S. COAST AND GEODETIC SURVEY
E. LESTER JONES, Director

UNITED STATES
COAST AND GEODETIC SURVEY

DESCRIPTION OF ITS WORK, METHODS, AND ORGANIZATION

Special Publication No. 23
(Revised Edition)

WASHINGTON
GOVERNMENT PRINTING OFFICE
1920

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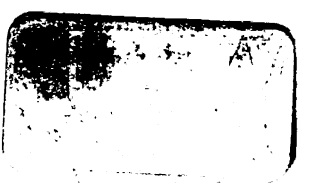

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Serial 135

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PREFACE.

Leaflets descriptive of the work of the United States Coast and Geodetic Survey were first published for distribution at the World's Columbian Exposition at Chicago, Ill., in 1893, and they have been revised, republished, and distributed at subsequent expositions in the United States.

This information, brought up to date, was issued in pamphlet form for distribution at the Alaska-Yukon-Pacific Exposition, Seattle, Wash., 1909. It has again been revised and brought up to date.

It will be seen on inspection that this pamphlet is intended to present concise statements relating to the origin of the Survey, to the general plan of its operations, to the methods and processes whereby the work is carried on, and to some of the more important results reached in its progress.

WASHINGTON, D. C., *July 1, 1920.*

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THE WORK OF THE UNITED STATES COAST AND GEODETIC SURVEY.

HISTORY AND ORGANIZATION.

To all nations whose territories touch the sea or who have any interests in the commerce of the sea a full and complete knowledge of the coast, its nature and form, the character of the sea bottom near it, the locations of reefs, shoals, and other dangers to navigation, the rise and fall of the tides, the direction and strength of currents, and the character and amount of magnetic disturbance are of the greatest practical value.

To supply this knowledge the Governments of the principal maritime nations have in modern times made surveys of their coasts by the most exact methods.

Some idea of the importance to this country of such operations may be formed when it is remembered that the coast line of the United States and Alaska, measured along its general trend, exceeds 11,500 miles in length. To represent the actual shore line, which includes all the islands, bays, sounds, and rivers in the littoral or tidal belt, these figures would have to be increased to 91,000 miles; and to the foregoing must be added the shore line of Porto Rico, Guam, Tutuila, the Hawaiian and the Philippine Islands, and the Virgin Islands of the United States. The length of the general shore line of these islands exceeds 5,400 miles, and their detailed coast line is in excess of 12,000 statute miles.

In 1807, during the administration of President Thomas Jefferson, Congress authorized the establishment of a national Coast Survey as a bureau under the Secretary of the Treasury, and the plan adopted for its execution was that submitted by Ferdinand R. Hassler. Because of the external relations of the country, it was impracticable to take any steps toward putting the plan in action until 1811, when Hassler was directed to proceed to Europe to arrange for the construction of the necessary instruments and standards, some of the most important of these being made after his own design. The outbreak of the War of 1812 seriously interfered with his commissions, their completion being thereby delayed until the close of 1815, and in consequence actual field work was not possible until 1816. The work was suspended in 1818 and resumed in 1832. For the purpose of fur-

nishing geographic positions and other data to State surveys, the scope of the bureau was enlarged in 1871, and in 1878 its designation became the Coast and Geodetic Survey.

On the organization of the Department of Commerce and Labor in 1903 the bureau was transferred to it from the Treasury Department, and in 1913 to the Department of Commerce.

The plan upon which it is at present organized is based on the broad scientific foundation proposed by Hassler and approved by Jefferson; and its present methods are the perfected results of experience gained in the field and office during more than a century of its existence.

Under the direction of a Director there are two great divisions of its work, the field and the office.

In accordance with the plan of reorganization of 1843, the work on shore was divided between civilian assistants and officers of the Army, and the hydrographic work was placed almost entirely in charge of officers of the Navy.

In 1861 the officers of the Army and Navy were detached, and since that date no officers of the Army have been assigned to duty on the Survey. After the Civil War the assignments of officers of the Navy gradually increased in number, so that the hydrographic work was about equally divided between them and the civil assistants during the period which extended to 1898, when the officers of the Navy, because of conditions created by the outbreak of the War with Spain, were finally relieved, and in 1900 Congress authorized the establishment of the Survey on a purely civil basis.

The Survey operates a fleet of 14 steamers and 1 motor vessel, of which 4 were built for the Survey, 5 were transferred from the Navy Department, and 3 are loaned by the Philippine Government.

The personnel of the Survey is at present divided as follows:

1. Field force, composed of 140 hydrographic and geodetic engineers, junior hydrographic and geodetic engineers, and aids, 11 magnetic observers, 17 tide observers, 59 mates, engineers, surgeons, deck officers, etc., 550 enlisted men, and an average of 160 additional employees who are necessary to insure the effective work of field parties on shore, besides a number of laborers hired for brief periods when needed.

2. Office force, composed of disbursing agent, chiefs of division, clerks, computers, draftsmen, engravers, instrument makers, printers, etc., numbering 229.

The office is that part of the establishment which receives the records, original sheets, etc., representing the results of field work. These are registered and deposited in the archives until in turn they are taken up for examination, computation, and adjustment, prepared for publication, and finally published. In the office charts are compiled from original surveys, by this and other government bureaus, and

printed by photo-lithography or by transfer from engraved copper plates.

For the convenience of administration the operations of the main office at Washington are carried on by six divisions, each having some specified portion of the general work to perform.

There is a field station at Manila, and the officer in charge, representing the Director, has authority to arrange for the conduct of insular field and office operations, to prepare and publish charts and sailing directions, and all other information which he decides is necessary or desirable for the use of mariners and the public generally.

There are field stations also at Boston, New York, New Orleans, San Francisco, and Seattle.

Because of the continental extent of the field of operations of the Survey a system of main and secondary triangulation, together with the determination of geographic positions by means of astronomic and geodetic methods, must furnish the foundations on which its results are based. On the Atlantic coast a scheme of primary triangulation begins at the eastern boundary of Maine and stretches to the Gulf of Mexico. A second extensive system of triangulation extends across the continent along the thirty-ninth parallel of latitude, connecting the surveys of the two coasts and furnishing a basis for the surveys of the 13 States through which it passes. Triangulation systems have been extended along the ninety-eighth meridian and along the Pacific coast from Canada to Mexico; from the ninety-eighth meridian in Texas across New Mexico, Arizona, and California, connecting with the Pacific coast triangulation; from the triangulation along the thirty-ninth parallel in Colorado northward to the Canadian boundary; and from the triangulation along the Atlantic coast to the Mississippi River at Memphis, Tenn.

In connection with these principal systems the triangulation has been considerably expanded in the New England States, New York, and several western States, including California, where some exceptionally large figures were introduced. The longest line on record so far observed is that from Mount Helena to Mount Shasta, which is over 190 miles in length.

A tertiary triangulation for topographic and hydrographic purposes has been completed along the entire Atlantic and Gulf coasts and that of Porto Rico and the Virgin Islands of the United States, and practically the whole of the Pacific coast except Alaska. Some progress has been made in the latter Territory, and in the Philippines the main triangulation has been practically completed.

In the determination of astronomic positions the exact methods originally developed in the Survey have been followed and perfected, and the methods of using the zenith telescope for latitude and the telegraph for longitude have been constantly improved.

Incidentally the triangulation and the astronomic observations connected with it furnish valuable data for the determination of the figure of the earth and the variation of densities in the earth's crust.

The topographic operations have been mostly restricted to a narrow margin, rarely more than 3 or 4 miles wide, along the coast and surrounding harbors, bays, and rivers to the head of tidewater.

The hydrographic operations have extended as far out from the coast as was necessary for the interests of navigation and have included all harbors, channels, bays, etc., as far as the work has gone.

Deep-sea soundings have been made extensively, especially in and about the Gulf Stream.

Much attention has been given to tides, and continuous series of tidal records have been obtained at important points.

The results of the operations of the Survey in connection with the study of terrestrial magnetism are shown on its charts and otherwise communicated to the public, in the fullest detail, in its numerous publications on the subject. In addition to the determination of the magnetic elements at many widely distributed points and their frequent redetermination at selected points for secular variation, instruments recording photographically are kept in continuous operation at five base stations for the purpose of obtaining a record of the ever-present fluctuations of the earth's magnetism.

The study of the force of gravity as a part of the great geodetic problem has received attention for many years, and the Survey has developed methods and instruments with which the work can be done at a greatly reduced cost and with a high standard of accuracy.

A network of precise levels, covering in a general way the entire United States, and connecting the Atlantic Ocean, the Gulf of Mexico, the Great Lakes, and the Pacific Ocean, has been run by the Coast and Geodetic Survey, the Corps of Engineers of the United States Army, the United States Geological Survey, and by the Pennsylvania and Baltimore & Ohio Railways. Much more leveling needs to be done to meet the demands of surveyors and engineers, and for this purpose the Survey has several precise-leveling parties in the field each year.

Throughout its history the Survey has constantly been called upon to determine boundary lines, both State and national.

In time of war the Survey has always cooperated actively with the military forces of the United States. During the War between the States, the Spanish War, and the late war in Europe practically the whole organization of the Survey was engaged in work required by the War Department or the Navy Department.

In order to make this cooperation more effective, an act was approved May 22, 1917, empowering the President, in time of national emergency, to transfer to the service and jurisdiction of the War Department and the Navy Department such vessels, equipment, stations, and personnel of the Coast and Geodetic Survey as he may deem for the best interests of the country. Provision was made by this act for the return to the

service and jurisdiction of the Department of Commerce of such vessels, equipment, stations, and personnel when in the opinion of the President such emergency had ceased.

Under the authority thus conferred on the President, five of the vessels of the Survey, with their complement of commissioned and other officers and enlisted men were transferred to the Navy Department by Executive order of September 24, 1917, and a number of commissioned officers and others were transferred to the Army; others volunteered or were drafted or otherwise entered some branch of the military service, and a total of 272 persons, comprising about 30 per cent of the total force of the Survey, including its Superintendent (now Director), rendered service in the Army or Navy. The commissioned officers of the Survey were commissioned as officers in the Army or Navy in grades corresponding to the positions held by them in the Survey. At close of hostilities these vessels, officers, and others were returned to the Survey.

The principal publications of the Survey consist of 659 different charts, covering all the coasts of the United States and its outlying insular possessions; annual tide tables for all the principal and many of the minor ports of the world, the most comprehensive volumes of this class issued by any country; Coast Pilots, containing sailing directions for all navigable waters along our coasts; special publications which give, in a form suitable for use by surveyors and engineers, the geographic positions and descriptions of triangulation stations, the elevations and descriptions of precise-leveling bench marks, and data for the magnetic stations; the annual report of the Director on the conduct of the work; and special reports upon the various technical and scientific operations of the service.

The one hundredth anniversary of the organization was celebrated in the city of Washington on April 5 and 6, 1916. Addresses were delivered by the representative leaders in the scientific, engineering, civic, and military life of the country. These have been collected and published in a single volume, thus furnishing a summary of the value of the operations and results of the first century of the Survey's existence.

TRIANGULATION.

The main object of a geodetic survey is to furnish the necessary control for all other surveys. This control includes the determination of the relative positions of some principal points of reference upon which to base the work. It involves the measurement of base lines and the measurement of the angles of the triangulation system. In other words, the distances and directions between certain points must be determined.

When the area to be surveyed is small or unimportant, the distances may be measured directly upon the ground, with chain or tape, and the directions may be obtained by the use of a compass or surveyor's transit. But when a survey is to cover an extensive territory or when great precision is desired, another method must be adopted. Aside from the difficulties and delays experienced in making accurate linear measurements upon even moderately level ground, the natural obstructions, such as bays, rivers, mountains, and forests, frequently render direct measurement impracticable. To overcome these difficulties the method called "triangulation" is employed. It rests upon the trigonometric proposition that if one side and the angles of a triangle are known, the remaining sides can be computed.

A line, forming a side of one of the triangles and called the base, is measured with extreme care. The angles of each triangle are measured and the distances between the points are then computed, one from another, through the successive triangles, proceeding in regular order from the measured line or "base."

Triangulations are usually classified as "primary" or "precise," "secondary," and "tertiary," according to their accuracy. No longer is a triangulation classified according to the sizes of the triangles involved. Primary triangulation is used in extending the fundamental control over the country and in accurate city surveys, such as those in New York and Cincinnati.

In the earlier days, when it was necessary to extend the primary triangulation across the country rapidly, very long lines were used whenever possible, these lines, in many cases, being over 100 miles in length. At present the economical length of line for primary work is considered to be from 25 to 40 miles. The length of line should be, as a rule, such that the total cost of the work of reconnoissance, building, and angle measurement will be a minimum per mile of progress. Primary triangulation is used as the framework for all other surveys. The accuracy of this class of triangulation is that represented by an average closing error of about 1 second of arc; that is, the sum of the three

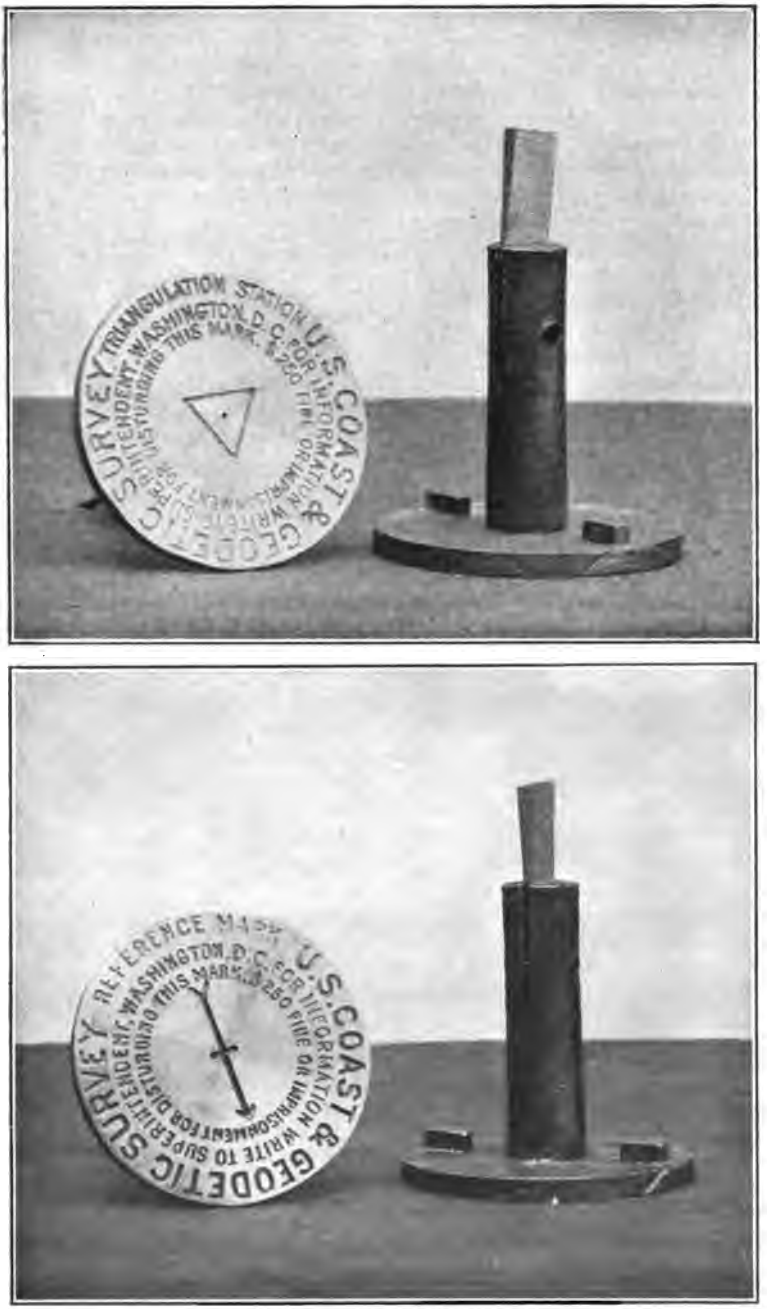


Fig. 1.—STATION AND REFERENCE MARKS.

measured angles of a triangle will, on the average, vary from 180° by not more than 1″. Of course, in large triangles a correction to the observed angles must be made on account of the curvature of the earth's surface.

The success of any triangulation depends to a great extent upon the reconnoissance, which is the most difficult and exacting task of an extensive survey. No two regions call for the same treatment, but some general considerations can be briefly outlined here.

Fig. 2.—COMPLETED TRIANGULATION TOWER.

A reconnoissance may be preliminary to minor triangulation along the seacoast, a river, or an estuary, where but a moderate degree of accuracy is required, and the range of selection of points is limited by the purpose for which the triangulation is to be used, namely, the control of a hydrographic or topographic survey along the shore. Or,

again, it may have to do with the arrangement of a great triangulation to cover a wide region. In the latter case, careful study will be required in order that the resulting project may best satisfy all the conditions. A reconnoissance for triangulation of the largest size is a matter of great complexity and demands great skill, experience, and judgment. It includes the collection of all information that will be valuable in the future operations of the building and observing parties, such as the proper selection of stations, location of base lines, and sources of supplies for the parties. Heavily wooded country is the most troublesome and makes it necessary to climb the tallest trees, or to raise poles taller than the trees, from which the distant horizon can be seen and such observations made as may be practicable. The most favorable country for a scheme of triangulation is a valley of proper width, with peaks on either side. It is possible then to select the proper stations with little clearing and building. Naturally the most elevated points will be chosen, provided their location will give the best shaped triangles, for the selection of low points might necessitate the building of high towers. A most important and difficult part of the reconnoissance is the determination of the heights of the towers necessary to make the line joining any two of them clear of all obstructions. These heights will depend on the relative elevation of the ground at the stations and of the intervening region.

When the reconnaissance of a region has been completed and the stations of the triangulation have been selected, the three angles of each triangle are carefully measured. Instruments, called theodolites, of various sizes, and stands or piers of different kinds are employed, according to the character of the country, the size of the triangulation, and the facilities at hand. These conditions also determine the kind of signals or objects to be used at the distant stations. At great distances the only objects which can be used are heliotropes by day and powerful lights by night. The heliotrope is a small mirror so arranged that it reflects the sunlight toward the observer. For some years automobile headlights burning acetylene gas have been used for night signals. Recently an electric signal lamp has been designed, principally for primary triangulation, the lamp being operated by dry-cell batteries. It has been found from experience that these electric signal lamps are much more powerful and can be seen when it would be impossible to observe the acetylene lamps.

The theodolites used in primary triangulation are instruments with well-graduated circles 12 inches in diameter. The circle is read to a second of arc by each of three micrometer microscopes, the mean of the readings constituting one observation of a direction. Were all the conditions perfect, a single careful observation of each direction would be sufficient. But the most excellent instruments have some defects, the most careful observers are liable to some slight error, and, above all, the line of sight, passing through miles of atmosphere of variable density and temperature, is subject to influences which defy analysis, and

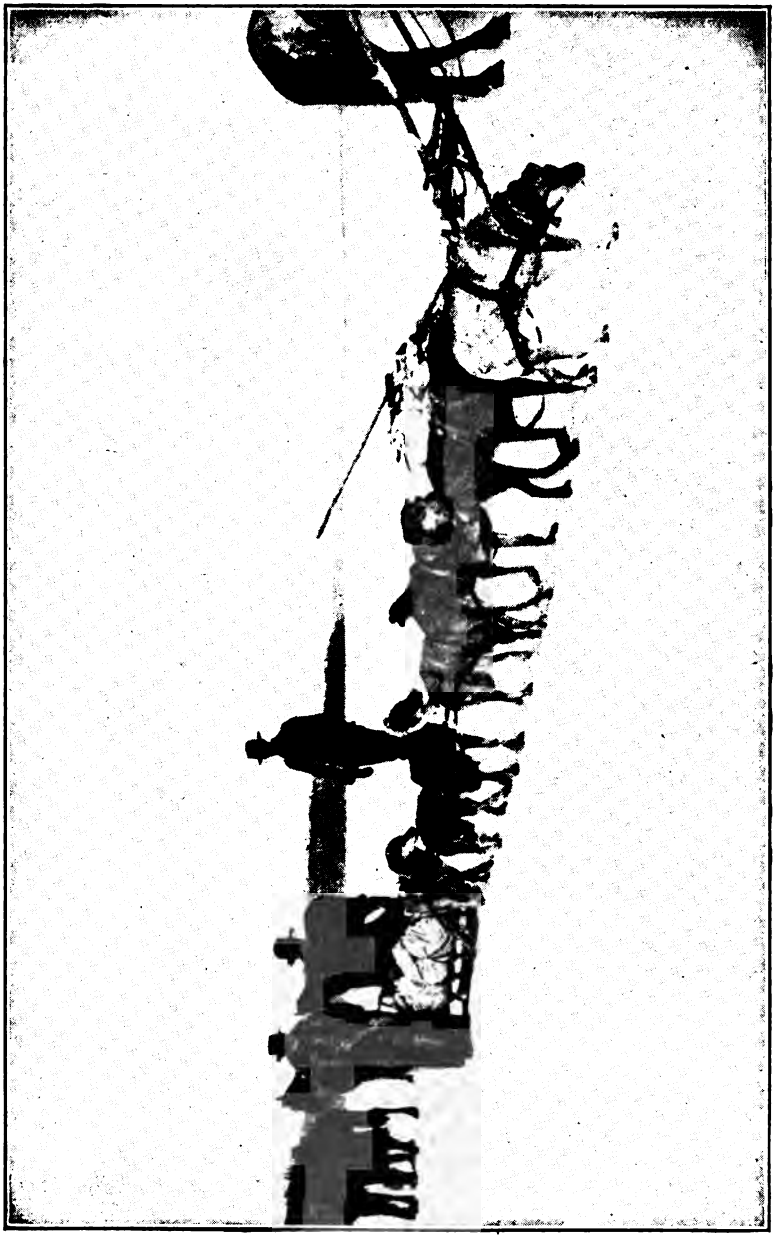


Fig. 3.—DOG AND HORSE SLEDS IN ALASKA.

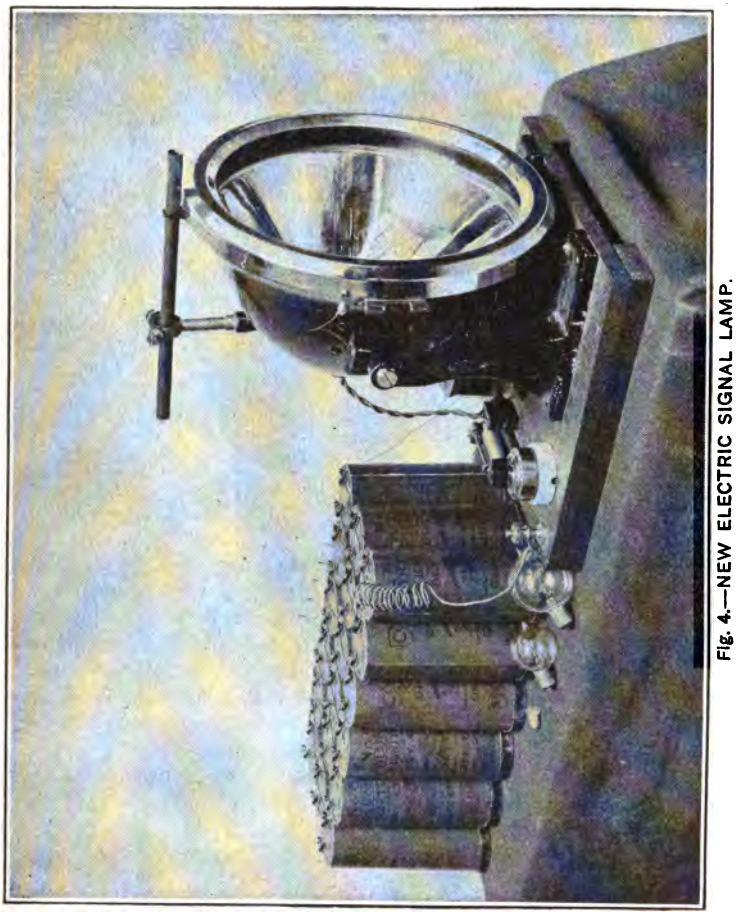


Fig. 4.—NEW ELECTRIC SIGNAL LAMP.

which can be neutralized only by making observations under different conditions. In order also to eliminate errors due to irregular graduation of the horizontal circle, these successive observations are made on different parts of the circle by shifting it through a definite portion of the circumference after each set of observations.

Recently an 8-inch Wanschaff theodolite has been used on some of the primary triangulation. It is lighter than the 12-inch instrument and greater speed can be obtained with it while still maintaining the required accuracy.

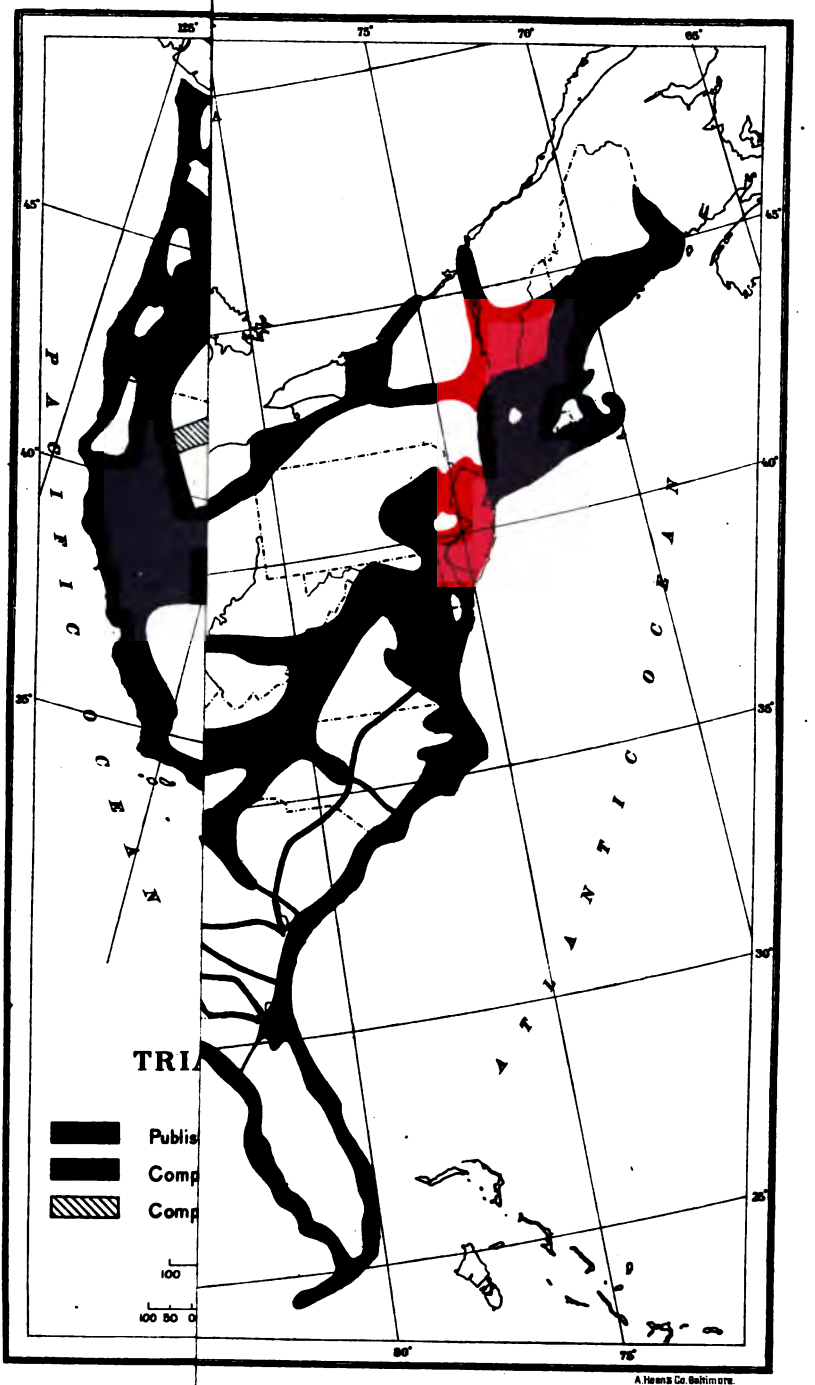
Triangulation with very long lines is possible only in regions of high mountains, where the curvature of the earth is overcome by the natural elevations. In lower country, heavily wooded, or where peaks of nearly uniform height are closely crowded together, triangulation must have more moderate dimensions, with lines from 10 to 40 miles long. In such country it will often be necessary to elevate the instrument from 20 to 60 feet above the ground, either on some existing building or upon a structure built for the purpose. While the practice in the Coast and Geodetic Survey is to limit to about 60 feet the height of any support especially built for the instrument, yet the heliotrope and lamp support is sometimes built as high as 125 feet above the ground. If the reconnoissance is well done, such heights as 60 feet for the theodolite and 125 feet for the heliotrope and lamps need not be exceeded, except in regions where the land is flat and the trees of excessive height.

By means of primary triangulation, the distance between two points may be obtained with an error of not more than one one-hundred-thousandth of the distance. For instance, if the distance is 100 miles the error will probably be less than 5 feet.

In secondary and tertiary triangulation the same general principles apply as in primary triangulation, but the details of the work will vary with the circumstances. Heliotropes and lamps are rarely used, and the angles are nearly always measured with smaller theodolites and a smaller number of measures are made. The accuracy of secondary triangulation is represented by an average closing error of a triangle of not more than 3 seconds of arc and that of tertiary by not more than 5 seconds.

In a tertiary system the object is primarily to furnish points for topographic and hydrographic surveys, and extreme precision is unnecessary because nothing else depends upon these points. Secondary triangulation is usually used in connecting the primary work with the tertiary.

After measuring the angles of any class of work the triangle sides are computed. The latitudes and longitudes of all stations are also computed by geodetic formulas, which are adapted to a particular spheroid representing the earth's size and shape. All distances determined by triangulation are referred to sea level.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In the survey of a city or other survey of limited extent, it is customary to use a system of rectangular coordinates based upon plane surveying in addition to the geographic coordinates—latitude and longitude. In the plane system all points are referred to an arbitrarily selected pair of rectangular coordinate axes instead of to the actual meridians and parallels.

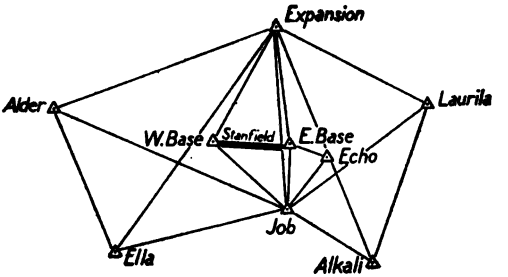


Fig. 5.—STANFIELD BASE NET.

It is possible, knowing the geographic coordinates of triangulation stations in a certain area, to obtain by simple formulas the rectangular coordinates. After an origin has been selected, all the directions are referred to the true meridian passing through it.

If the triangulation is to serve any further purpose, it is very essential that the stations be marked in a permanent manner. The practice in this survey is to have at every station a standard metal triangulation mark, which, if practicable, is set in rock or concrete. (See fig. 1.) There is also placed an underground mark which is separated from the surface mark. In addition there is set at least one reference mark, which is referred to the station by an angle and distance. This reference mark is not only important in serving in place of the station mark if the latter is destroyed, but it aids in the recovery of the station mark. If the station mark is in bedrock it is surrounded by a triangle cut in the rock, so that it will be possible to recover the station approximately if the metal disk has been removed.

It is especially important in the execution of a triangulation scheme that careful and accurate descriptions of all stations be made. The description should enable one who is unfamiliar with the locality to find the exact point determined and to positively identify the monuments marking the station.

Figure 6 (see folded map) shows the progress of the control triangulation in the United States. This triangulation was done by the U. S. Coast and Geodetic Survey, Corps of Engineers (U. S. Army), International Canadian Boundary Commission, and other organizations.

See also: General Instructions; Appendix 4, Report for 1903; Appendix 4, 1911; Special Publication No. 19.

BASE LINES.

In a triangulation it is necessary to determine by direct measurement the length of one of the lines of the scheme from which to start. From this line, as a base, and the observed angles a computation will give the lengths of the other lines of the triangulation. It is usual in an extensive scheme to have direct measurements of one or more additional triangle sides to strengthen the computed lengths and to guard against gross errors. The direct measurement of those sides of the triangles used as bases has been a difficult problem for surveyors and geodesists until recent years. At present the bases can be measured with great accuracy by means of tapes or wires made of the alloy of nickel and steel called invar.

Among the earliest forms of measuring apparatus used were wooden bars and glass tubes. These were not satisfactory, and they gave way gradually to metal bars, which apparently were first used in 1788 in Italy, and a little later, in 1798, in France.

The bars were usually made of steel or brass, and they maintained their lengths most satisfactorily, but the great difficulties involved were the determination: (1) Of their exact lengths in terms of some standard unit, at some given temperature; (2) of the amount of change in length for a given change in temperature; and (3) of the exact temperature of the bars during the field measurement. The first difficulty was overcome by standardizing the bars in a room which could be maintained at a constant temperature, and the coefficient of expansion was determined by standardizing the bars in the room at widely different temperatures. It was impracticable to obtain the temperature of the single-rod bar during field measurements in daylight with a high degree of accuracy. Many methods of insulating and protecting the metal rod were employed, but the temperatures read from the mercurial thermometer inserted in the case did not correctly indicate the actual temperature of the rod.

A base measured with single brass or steel rod bars, with a small probable accidental error, might have a large actual error. As an example, a base measured by a set of these bars in Colorado, with a probable accidental error of only 1 part in 752,000, was, in 1913, remeasured with invar tapes and the difference in the two lengths was 1 part in 59,000.

It is probable that steel or brass single-rod bars would give more accurate results if used only on cloudy days, or if they were used at night, when the temperature is apt to be more constant, for then the temperature given by the thermometers would be more nearly that

of the bars. But cloudy days in some regions are not numerous, and to have measured a base at night would have been a difficult and tedious undertaking.

In order to minimize or eliminate the effect of errors in temperature, various compound bars were devised. One type consisted of two parallel rods of different metals, such as platinum and copper, or steel and brass, the two rods of a bar having very different rates of expansion. Theoretically, the average temperature could be obtained by noting the difference in length of the two components, which were arranged with suitable scales for making the comparison. This principle of differential expansion was applied in several different ways. Other compound bars were designed to give a constant length by a compensating arrangement of the components.

Excellent results were obtained with the Bache-Wurdemann compensating bars of the Coast and Geodetic Survey, but it was found that slightly different results were obtained with rising and with falling temperatures. This trouble was minimized by having the bars standardized under each condition. The Eimbeck duplex bars of the Survey also gave a high degree of accuracy in the measurements, but they were not used much, as the use of the tapes was begun shortly after they were made.

In the field measurements the bars were supported by portable tripods. The bars were either "line measures" or "end measures." In the first type the length of the bar is the distance between two very fine lines engraved on the top of the bar near its ends. The successive bar lengths were referred to powerful microscopes mounted on posts set along the line of the base. In the "end measures" the length of the bar is the distance between its ends, and the procedure was to set two bars end to end and then move the rear one ahead and bring its rear end into contact with the forward end of the bar left in place. In one of the earliest methods of measuring, the two bars were brought nearly together, and the distance between them was measured by a wedge properly graduated and standardized. The wedge was inserted between them and the points of contact of the bar ends on the wedge would enable the distance between the bars to be determined accurately. These small distances would be added to the whole number of bar lengths. The usual and better method of making the contact of the two bars was to have a sleeve fit over one end of each bar, the sleeve being connected with the bar by a spring. The bar was normal when a graduation on the sleeve coincided with a graduation on the bar. A slow-motion device enabled the operator to move the forward rod in its case until the contact with the rear bar was perfect and the two graduations on the bar and sleeve coincided. This procedure was repeated throughout the length of the base.

The only bar used in the United States, and probably in the world, which will give entire satisfaction in so far as accuracy is concerned is a "line measure" called the "iced-bar apparatus" of the Coast and

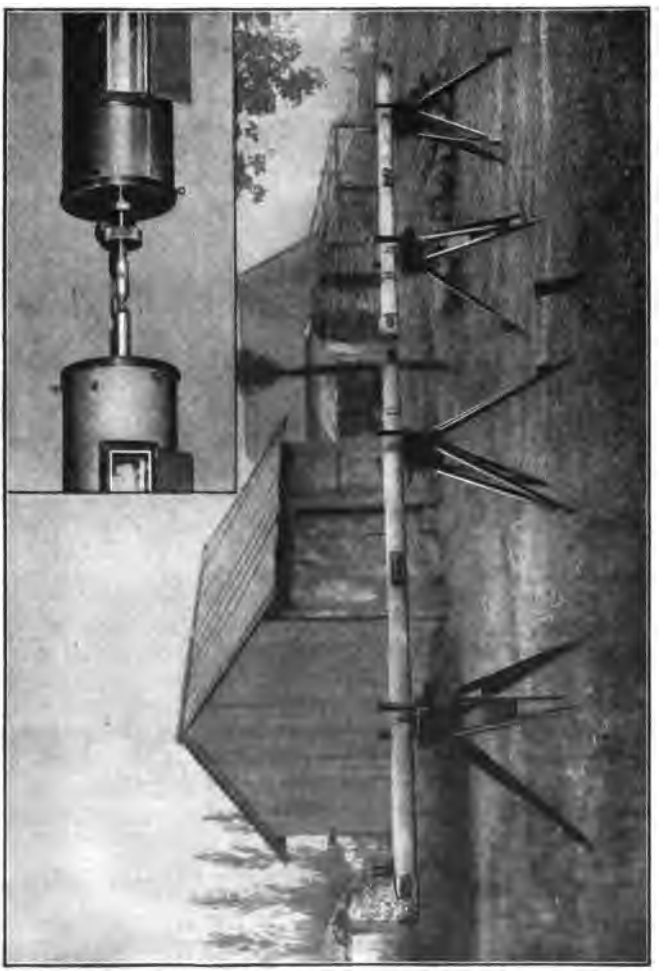


Fig. 7.—DUPLEX BASE APPARATUS.

Geodetic Survey, which was designed by Dr. R. S. Woodward. During measurements this bar is placed in a trough which is filled with crushed ice. Thus the bar is kept at a uniform and definite temperature, that of melting ice. Of course, measurements can not be made when the temperature of the air is below the freezing point. The trough is mounted on a carriage which runs along a portable track. The successive bar lengths are referred to microscopes placed on posts set along the base. The cost of using this bar in the field is prohibitive, and it has been and is now used only for the purpose of standardization of other apparatus, and for this it is unexcelled.

Steel wires and tapes were used in general surveying long before they were used for the measurement of primary base lines. They were apparently first used successfully for bases by Prof. Jaderin, of Sweden, about 1882. Tapes were experimented with at the Holton primary base, Indiana, in 1891, and found to be as accurate when used at night and much more economical than bars. Tapes were used in 1893 and 1897 in measuring the bases at St. Albans, W. Va., and at Versailles, Mo. In 1900–1901 steel tapes of 100-meter and 50-meter lengths were used in connection with the Eimbeck duplex bars in the measurement of nine primary bases on the ninety-eighth meridian. The result of this campaign proved conclusively that the tapes used at night gave an accuracy as great as that obtained with the best bars.

In 1906 the Survey tested tapes made of the alloy of nickel and steel (called invar) by measuring six primary bases with both steel and invar tapes. The invar tapes gave results of even greater accuracy than the steel tapes, although the former were used in daylight, while the latter were used at night. All of the tapes were 50 meters in length, this length having been found more satisfactory than 100 meters during 1900–1901.

The average coefficient of expansion of the invar tapes used by the Survey is only 0.0000004 per degree Centigrade, or about one-twenty-fifth that of steel. Having available a metal with such a low coefficient of expansion, the great problem in base measurement has been solved. Bars of this metal would no doubt give a measurement almost without error, but invar tapes give results which have actual errors little or no greater than one part in one million, and, as a base can be measured with tapes for 35 per cent or less of the cost of bar measurements, it is practically certain that no more base lines will be measured with bars. Tapes have the additional advantage that they may be used over broken ground and steep slopes where bars could not be used.

The data available indicate a remarkable constancy in the values of the lengths of the invar tapes used in recent years. It may be stated also that the invar tapes are not so susceptible to injury during field work as was supposed to be the case soon after their introduction. Each of the base parties which used the tapes under discussion had

only two members who were skilled in the use and treatment of tapes, the other persons in the party being unskilled men. The members of each party were cautioned to use every care in handling the tapes, but, even so, it seems remarkable that not one of the tapes has been injured.

Invar wires are used in some of the other countries with great success. The advantages of wires over tapes about equally balance the advantages of the tapes over the wires. Each type of apparatus will give results far greater in accuracy than that required. The wire is less affected by the wind. The tape is more easily reeled and unreeled than the wire. The wire may become twisted without detection, while this seldom happens with the tape. The wire seems to be more subject to kinks than the tape. Owing to the lesser thickness of the tape, a smaller diameter may be used for its reel than for the reel of the wire.

The method of supporting the tape or wire during measurements, of applying the tension, and of marking successive lengths varies greatly. Each method has its advocates and special advantages. The method employed in the Coast and Geodetic Survey is to set stakes firmly throughout the length of the base. At 50-meter intervals (the length of the tape) a stake 4 inches in cross section is used. The intermediate supports are nails driven horizontally into stakes set just off the line. Usually only one intermediate support is used, and, except in rare cases, its top is in a straight line with the tops of the two end supports. The tape lengths are transferred to copper strips nailed to the tops of the end supports, the strips being of the same thickness as the sleeves of the tape which carry the graduations. The tension is given by a spring balance attached to a stretcher. A line of levels is run over the base in both directions to get the grades from which corrections to give the horizontal distance are computed. The setting of the stakes and the leveling may be done in even strong winds, while the calmest days are utilized for measuring with the tapes.

It is customary to divide the base into sections of about a kilometer in length and to measure each section twice, using a different tape for each measurement. The two results to be acceptable must have a smaller discrepancy than 20 millimeters times the square root of the distance in kilometers. The mean of the two measurements is taken as the final length. Usually three different tapes are used for each base, different combinations of two of the three tapes being used on different sections in such a way that each of the three tapes is used in one-third of the measurements. The probable error in the measured length of a primary base line is usually less than 1 part in 1,000,000.

The base party usually consists of six persons, and only one needs to have had previous experience in the work. In fact, the measurement of even a primary base is so simple an operation that this work is now considered a mere incident of the triangulation and is done by the triangulation party. This plan has two decided advantages: First, the lengths of the bases will be known when the triangulation of an

arc has been completed; and, second, the base work can be done at much lower cost than where a party is especially organized and outfitted for measurement of bases.

The average field cost of measuring a base by the triangulation party is about $50 per kilometer. The cost by special parties may be 50 per cent greater than this. The cost of the measurements with base bars varies greatly, but the minimum was several times greater than that with the tapes.

See also the following publications of the Coast and Geodetic Survey: Appendix 8, Report for 1892, On the measurement of the Holton base, Indiana, and the St. Albans base, West Virginia; Appendix 3, 1901, On the measurement of nine base lines along the ninety-eighth meridian; Appendix 4, 1907, Six primary bases measured with steel and invar tapes; Appendix 4, 1910, The primary base lines at Stanton, Tex., and Deming, N. Mex.

PRECISE TRAVERSE.

Traverse is a surveying operation designed to furnish the latitudes and longitudes of a number of points which form the control or base stations for detailed surveying operations. Traverse is used in those areas which are so flat or so heavily wooded that it would be excessively expensive to carry on triangulation (see pp. 10 to 17) owing to the necessity of having high signals to elevate the surveying instruments above intervening obstructions. The traverse lines nearly always follow railroads and, therefore, very little signal building and clearing of lines are necessary.

Precise traverse, as carried on by the United States Coast and Geodetic Survey, consists practically of a series of base lines placed end to end. The measurement of each of the lines is made with almost the same accuracy as is used on primary base lines. (See p. 22.) The angle formed by each two contiguous lines of traverse is measured in the same way as in primary triangulation, but only about one-half as many measurements of the angle are made. The observations are made on poles instead of heliotropes and lamps, as the lines between traverse stations are shorter than in primary triangulation. The probable error of the measurement of an angle is about double that of primary triangulation. (See pp. 10 to 17.)

Traverse was used very little in control surveys by the Coast and Geodetic Survey previous to the year 1917. Since that year an elaborate system of precise traverse lines has been established in Georgia, Virginia, North Carolina, South Carolina, Florida, and Louisiana, for the purpose of furnishing control for military and other maps in the parts of the country through which the lines run.

A section of a line of traverse usually consists of the distance between the intersections of a tangent with the two contiguous tangents of the railroad. A tangent is the technical name of a straight piece of track of a railroad. At each of the intersections of two contiguous tangents is located a station of the traverse, but occasionally when a tangent is very long or the profile of the railroad is such that it would be difficult to observe between the two ends of a tangent, one or more stations are placed to the side of the railroad. Usually the traverse stations are not more than 5 miles apart. Whenever a traverse runs through a town of considerable size, at least two traverse stations are established close to it in order that the results may be used by the local engineers and surveyors in their work.

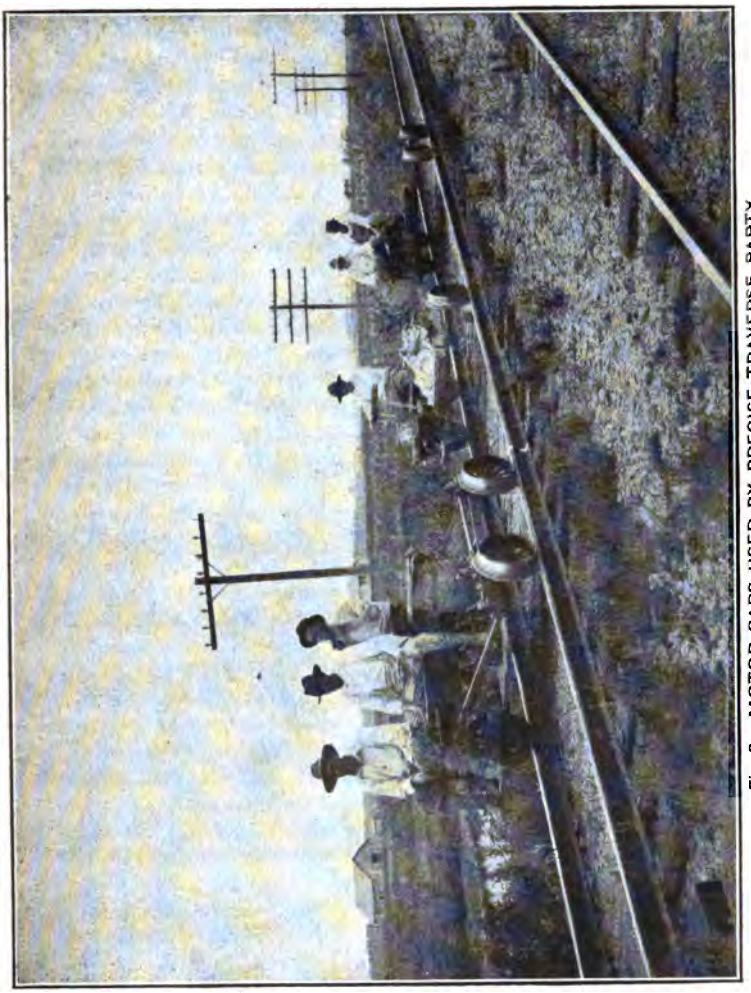


Fig. 8.—MOTOR CARS USED BY PRECISE TRAVERSE PARTY.

The length of each of the lines of the traverse is measured with great accuracy with a regular base tape 50 meters in length made of nickel-steel alloy, commonly called invar (an abbreviation of invariable). The advantage of using this metal is that its expansion and contraction with changes in temperature are very small as compared with steel and other common metals. There are two marks on the tape, one at each end, which are almost exactly 50 meters apart under standard conditions. The exact difference between the distance from one mark to the other and 50 meters is determined at the Bureau of Standards.

The tape is used on the traverse under exactly the same conditions, as far as practicable, as obtained when the tape was standardized at the Bureau of Standards before being sent to the field. What is desired is the horizontal distance between the ends of the tape when it is stretched out. In order to have this it is necessary to know the difference between the temperature of the tape when the measurement is made and the temperature of the tape when it was standardized. The temperature of the tape is obtained from readings of two thermometers attached to the tape during the measurements. From this it is possible to compute a correction to the measured distance. If the temperature is higher than the standard temperature the correction must be added, while if the temperature is lower than standard the correction must be subtracted. Another correction that is necessary is for the inclination of the tape or grade. It is readily seen that if the measurement is made on a slope the distance between the ends of the tape will be greater than the corresponding horizontal distance between the ends. It is necessary to apply the same pull on the tape that was used during the standardization. This pull is usually 15 kilograms (about 33.1 pounds), and is applied by a spring balance attached to one of the two especially designed stretchers. When this tension has been applied and the tape is held on the top of the rail it assumes practically a straight line between its ends. If the tape is not stretched with this rather high tension, it is easily seen that the small bends in the tape would make it impossible to get an accurate measurement.

There is usually a distance of several hundred feet from the point at which the curve begins at the end of a tangent to the traverse station. Along this distance there are placed stakes to support the tape during the measurement. When measuring over the stakes the forward end of the tape is marked on the stake by means of a pin or a scratch made with a knife or some other sharp-pointed instrument. Occasionally a narrow strip of copper is nailed to the top of the stake and the end of the tape is referred to that by a scratch on the copper.

While measuring along the tops of the rails the rear mark on the tape is brought into coincidence with some mark that has previously been made on the rail (see fig. 9), and the mark on the forward end of the tape is transferred to the rail by a glass cutter.

The accuracy with which a line of traverse is measured with the invar tape is about one one-hundred-thousandth of the distance measured.

For instance, if the distance is 1 mile, the error in measurement of the distance would be only about two-thirds inch.

The grade or inclination corrections to reduce the measured distance to what it would have been if the rail had been horizontal are obtained from the results of a line of precise levels which is carried along the rail. This leveling determines the elevations of the traverse stations, the points of tangency on the rail, the rail opposite any traverse station that is not at the intersection of two tangents, and any point where the grade of the railroad makes a decided change, that is, where there is a depression or a hump in the track.

In addition to other corrections it is necessary to apply one which will reduce the horizontal distance between two stations to what it would have been if it had been measured at sea level. It is readily seen that in order to have the control surveys, extending over a large area, accurately fit the earth and not be distorted, all distances must be referred to sea level. All that is necessary in order to reduce the distance to sea level is to know the average elevation of the line, the general direction of the line, and the shape and size of the earth.

The traverse line usually starts from some station of the triangulation net of the country whose latitude and longitude and the azimuth of one of the triangulation lines radiating from it have been determined. After the distances and angles of the traverse have been measured, the geographic positions of each of the stations of the traverse can be computed and the azimuths of the lines of the traverse can also be obtained by combining the angles measured along the traverse with the azimuth of the line of the triangulation from which the traverse is started. At frequent intervals along the traverse the azimuth of a line must be determined astronomically by observations on Polaris.

At the office of the Coast and Geodetic Survey in Washington an adjustment of the traverse line is made to fit it into the general network of the triangulation and traverse lines of the country in order that there will be no inconsistencies in the work. In the adjustment the astronomic azimuths that are observed along the line of traverse are used to control the geodetic azimuths which are carried through the measured angles from the preceding azimuth station or from the line of triangulation where the traverse started.

In all measurements in surveying it is wise to have such methods as will make it possible to discover mistakes in the work. In order to guard against mistakes in the measurement of the traverse lines with the 50-meter invar tape, a rough measurement is made with a 300-foot steel tape. The measurement with the latter is rather crude in comparison with the work that is done with the invar tape but it is of sufficient accuracy to discover any large mistakes, such as added or dropped tape lengths or a setback for set-up, or vice versa. Set-ups and setbacks are distances in the traverse line which are shorter than a full tape length. It is seen that it would be impossible to make a mistake in each measurement which would have exactly the same value when tapes of different lengths and different units are used.

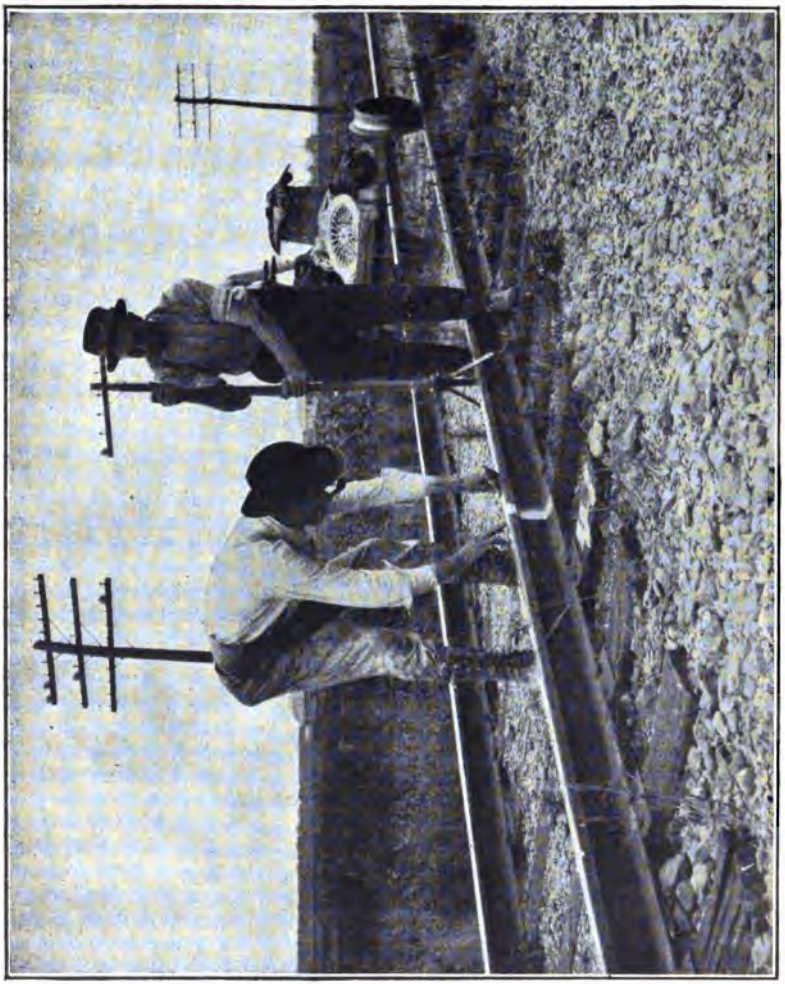


Fig. 9.—PRECISE TRAVERSE PARTY MAKING THE REAR CONTACT.

As in triangulation, each traverse station is marked by a metal disk, properly inscribed, set into solid rock or especially constructed blocks of concrete. (See p. 17 and fig. 1.)

It has been found that the accuracy which can be obtained with precise traverse is as great as that obtained by primary triangulation. (See p. 16.) It is reasonably certain that the distance between any two points of a traverse which has been adjusted for azimuth and loop closures is known within about 1 part in 100,000.

The traverse has the advantage over triangulation by having its stations much closer together and in places that are more accessible, and therefore can be used by the surveyors and engineers to greater advantage. Besides, the traverse lines are run along railroad tracks where transportation of parties, instruments, and equipment is easier than in triangulation. Small motor cars are generally used to transport the parties. (See fig. 8.) On the other hand, triangulation has advantages over traverse because of the fact that its stations are usually on high points and thus are visible from much larger areas than is the case with stations of the traverse. Besides, the triangulation stations are usually 10 or 15 miles apart, and it can be seen that in carrying on an arc of triangulation a belt of country of approximately 10 or 15 miles in width is controlled, while with the traverse there is only a single line.

After the completion of the work in the field and the office, the results of the precise traverse, consisting of the geographic positions of the stations, the distances and azimuths of the lines, and the descriptions of the stations, are published in pamphlet form for the use of engineers and map makers.

The Coast and Geodetic Survey has not carried on any secondary traverse, although it has perfected methods to be used in this class of work in place of secondary triangulation wherever the conditions make it more economical to do so. The secondary traverse is almost exactly similar in character to the precise traverse, except that the methods used are not quite so refined.

Anyone who wishes to study the traverse work and methods of the United States Coast and Geodetic Survey is referred to Special Publication No. 58 of that organization entitled, "General Instructions for Precise and Secondary Traverse."

ASTRONOMIC WORK.

The United States Coast and Geodetic Survey has carried on astronomic work in the United States and its possessions, including the Philippines and Alaska, for many years. The purpose of this work is to give the location of cities, islands, and other widely separated places in connection with the surveying and mapping of the coasts and interior of the country, to locate the stations at which magnetic observations are taken, and to supply certain data needed in the adjustment of the triangulation net of the country.

Astronomic work consists of the determination of time, latitude, longitude, and azimuth. These four classes of work are described in separate sections below.

TIME.

The time observations made by the engineers of the Coast and Geodetic Survey are, in general, of two classes, depending on the accuracy required. For the less accurate work observations are made on the sun or stars by means of a sextant or vertical circle. With these instruments the angular distance of the sun or of a star from the zenith, the point directly overhead at the place of the observations, is measured and, at the instant the observation is made, the time is read on a chronometer or watch. Other data needed in the determination of local time—that is, the determination of the error of the chronometer or watch—are the approximate latitude, and, for observations on the sun, the approximate longitude of the station at which the observations are being made. The coordinates of the star's position, namely, its angular distance from the Equator, called declination, and its angular distance from the hour circle through the vernal equinox, called right ascension, are needed for the computations and may be found in the American Ephemeris and Nautical Almanac, published by the Naval Observatory, Washington, D. C., or in similar books published by other countries. In order that the effects of refraction and instrumental errors may be eliminated from the results to a great extent, observations are made on a star to the eastward of the station and on another to the westward. The error of the determination of time with a sextant or vertical circle is approximately one-half second.

In the most refined work of the Coast and Geodetic Survey time is determined with an instrument called an astronomic transit. This instrument is shown in figure 12. Descriptions of it may be found in Special Publication No. 14 of the Coast and Geodetic Survey or in any textbook on geodetic surveying and astronomy. In its general principles it is somewhat similar to the ordinary surveyor's transit, except

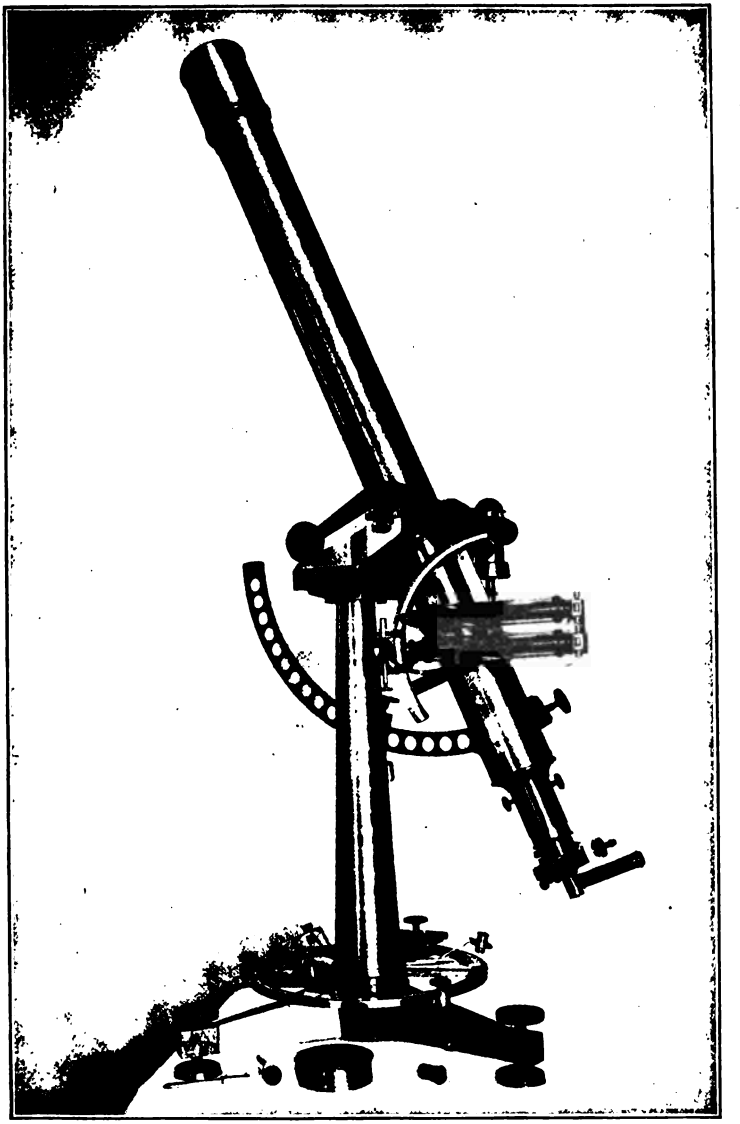


Fig. 10.—ZENITH TELESCOPE USED IN LATITUDE DETERMINATIONS.

that it is much larger and has no circle for reading horizontal angles. It consists of a telescope with a rotation axis rigidly attached at right angles to it and terminating in pivots which are supported in two wyes or standards. The telescope contains wires placed in the focus of the objective, so that the image of a star at which the telescope is pointed will be in the same plane as the wires. The eyepiece of the instrument consists of a simple lens or combination of lenses which magnify the wires and the image of the star in order to make them visible to the observer.

When the instrument is in adjustment, the line joining the center vertical wire in the telescope and the center of the objective lens is at right angles to the horizontal axis of the telescope, the horizontal axis of the telescope is truly horizontal, and the vertical plane described by the line of sight as the telescope is swung on its horizontal axis is coincident with the plane of the meridian. It is impossible to have the adjustment of an instrument absolutely perfect and, therefore, methods of observing are followed which will eliminate, or at least greatly minimize, the errors due to the lack of perfect adjustment.

Twenty years or more ago the usual method in the determination of time with the astronomic transit was to record the time as shown on the chronometer when the star passed each one of a number of vertical wires in the telescope. There were two general methods for making the observations, one called the eye-and-ear method and the other called the key method. In the first method the observer listened to and carried the seconds beat of the chronometer in his mind while watching the star cross the wires in the telescope and thus was able to note the time of crossing each wire. In the second method, each time the star crossed a wire the observer pressed a key which broke an electric circuit through a chronograph and thus recorded the time on the chronograph sheet.

The chronograph, as the name implies, is an instrument for "marking" or recording time. (See fig. 13.) It has a drum revolving at a uniform speed on which a pen or pencil traces a line in the form of a helix. The pen is operated by an armature which causes it to make a jog in the line whenever the electric circuit is broken. The chronometer is connected in this circuit and automatically breaks the circuit every second except the fifty-ninth of each minute. The line on the chronograph sheet will therefore show a jog or notch for each second of the chronometer except the fifty-ninth, and an extra notch for each time the circuit is broken by the key. The exact time when the key was operated can therefore be scaled directly from the chronograph sheet. (See fig. 15.)

The modern method of noting the times of transit of the star across the field of the telescope is that of the self-registering micrometer. In this micrometer is a movable thread which can be made to follow the star as it crosses the field. By means of a series of automatic electric contacts in the micrometer eyepiece a record of the star's passage

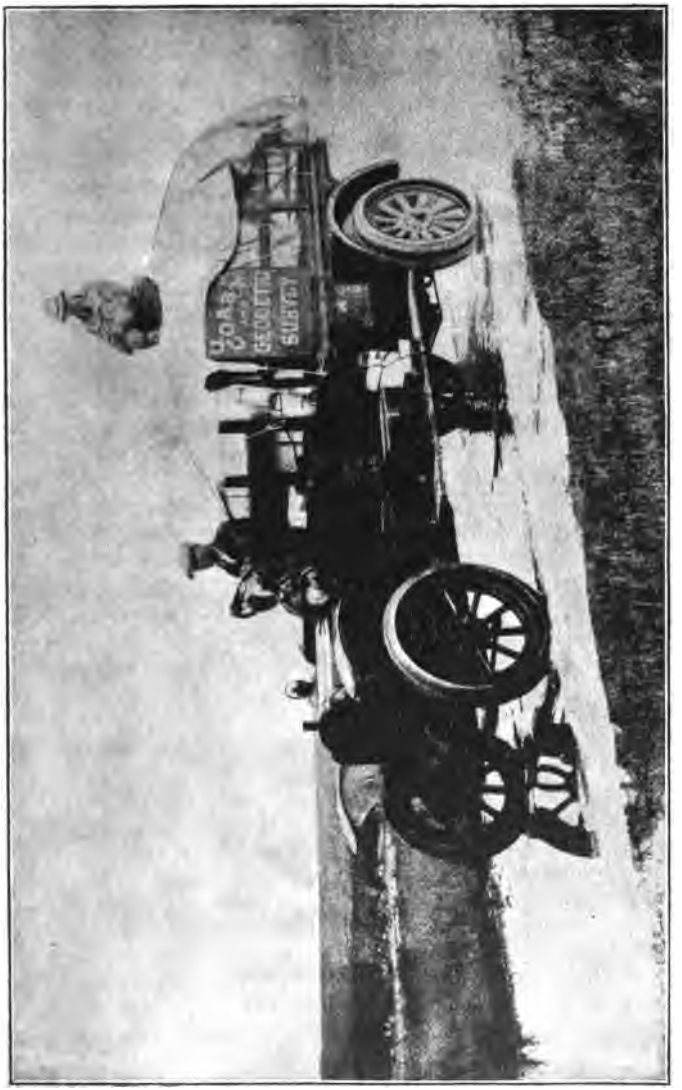


Fig. 11.—AUTOMOBILE TRUCK USED FOR TRANSPORTATION OF FIELD PARTY.

across the meridian is made automatically on the chronograph as described above.

The great advantage of the automatic method of recording the time at which the star passes the meridian is that it eliminates what is called personal equation, which is present in the eye-and-ear and also in the key method. The personal equation is an error unconsciously made by the observer in constantly observing either too soon or too late the passage of a star across the wires. The more expert the observer, the more nearly constant is his personal equation.

Since the right ascension of a star is the local sidereal time of its passage across the meridian, the error of the chronometer may be easily computed from the data furnished by the observations described above. The details of the methods employed in making these computations are given in Special Publication No. 14, of the United States Coast and Geodetic Survey, entitled, "Determination of Time, Longitude, Latitude, and Azimuth."

A determination of time with an astronomic transit usually consists of observations on five or six stars which are especially selected to form a group. The probable error of a determination of time from such a group is usually not greater than about .02 second. This accurate time-work of the United States Coast and Geodetic Survey is done almost exclusively for the determination of longitude and in connection with the determination of the intensity of gravity. (See p. 94.)

LONGITUDE.

As is well known, the position of a place on the earth's surface is expressed in terms of latitude, the angular distance north or south of the Equator, and of longitude, the angular distance to the east or west of some adopted initial meridian. The meridian that is in almost universal use at the present time is the meridian which passes through the observatory at Greenwich, England. A meridian is simply an imaginary line formed by the intersection of a plane with the earth's surface or with the celestial sphere. This plane contains the earth's axis and is at right angles to the plane of the Equator.

The determination of the longitude of a place consists, therefore, in measuring the angular distance between the adopted initial meridian plane and the plane of the meridian through the place whose longitude is sought; or it may consist in the determination of the angular distance between the meridian through some place already referred to the initial meridian and the meridian through the new station.

The angle between any two meridians can be expressed in degrees, minutes, and seconds of arc or in hours, minutes, and seconds of time. There is a simple relation between these two measures. An hour is equivalent to 15°, a minute of time is equivalent to 15′ of arc, and a second of time to 15″ of arc. With this known relation between time and arc we have a means by which to determine the difference of longitude. This consists simply in determining the difference between the

local times at the two places, one where the longitude is known, and the other where it is unknown.

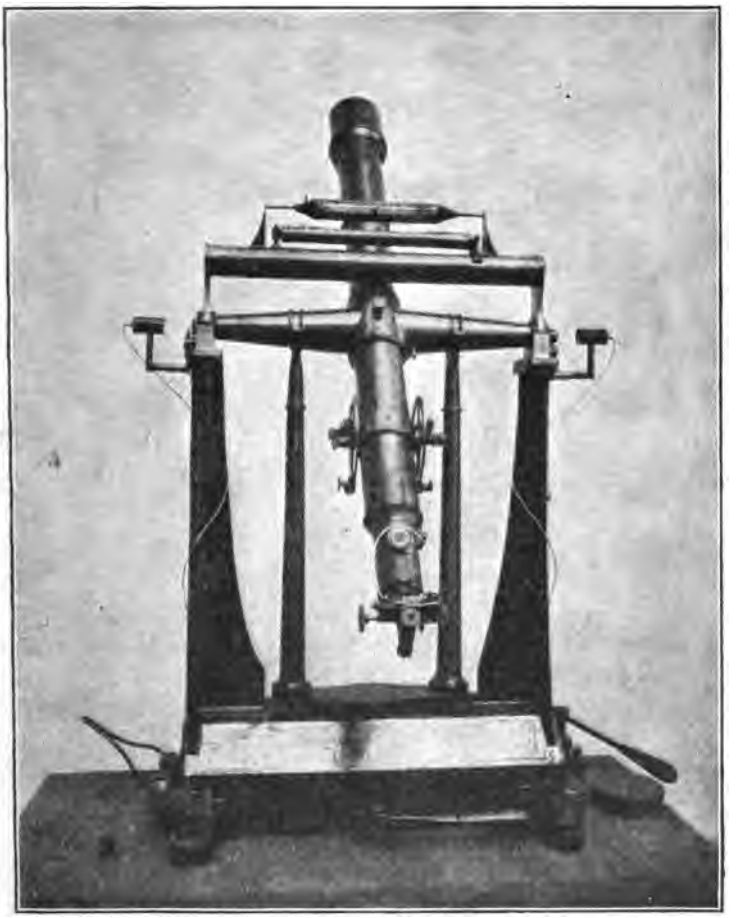


Fig. 12.—LARGE PORTABLE TRANSIT WITH TRANSIT MICROMETER USED IN TIME AND LONGITUDE WORK.

Before the invention of the electric telegraph it was necessary in determining a difference of longitude to transport a chronometer set to the local time of a place where the longitude is known, as for instance, Greenwich, New York, Paris, or some other place, and compare this time with the local time as determined by observations at the new station. This is the method still used by navigators.

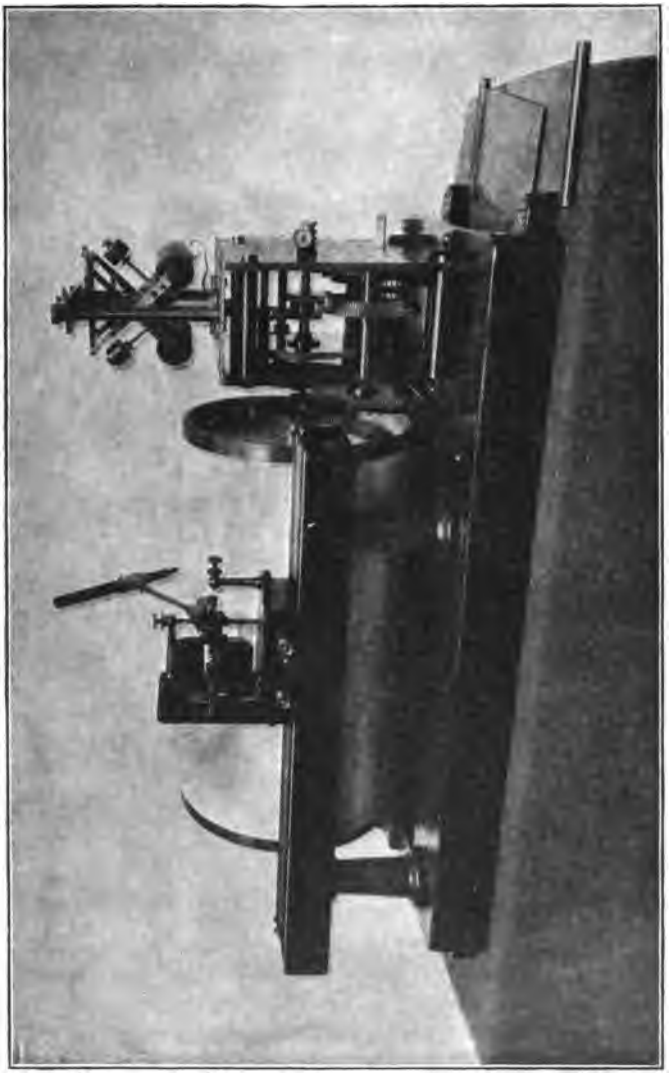


Fig. 13.—CHRONOGRAPH FOR TIME AND LONGITUDE WORK.

Other methods of determining the differences of longitude are to observe the local time that the moon crosses the local meridian, or that stars are occulted by the moon, or that the eclipse of a satellite of Jupiter occurs. While these methods avoid the uncertainty in the rate of the chronometer when carried from one place to another, the resulting differences of longitude are not of a high degree of accuracy and the computation of the local time and the Greenwich time at which the observations take place is a laborious process.

Another method that has been used by explorers in the determination of longitude is that of observing flashes of light on mountains. These flashes are made by mirrors reflecting the light of the sun or by explosions of powder. The two observers note their local times at which the flash occurs and later the information is sent by each observer to the other and the difference in time becomes known.

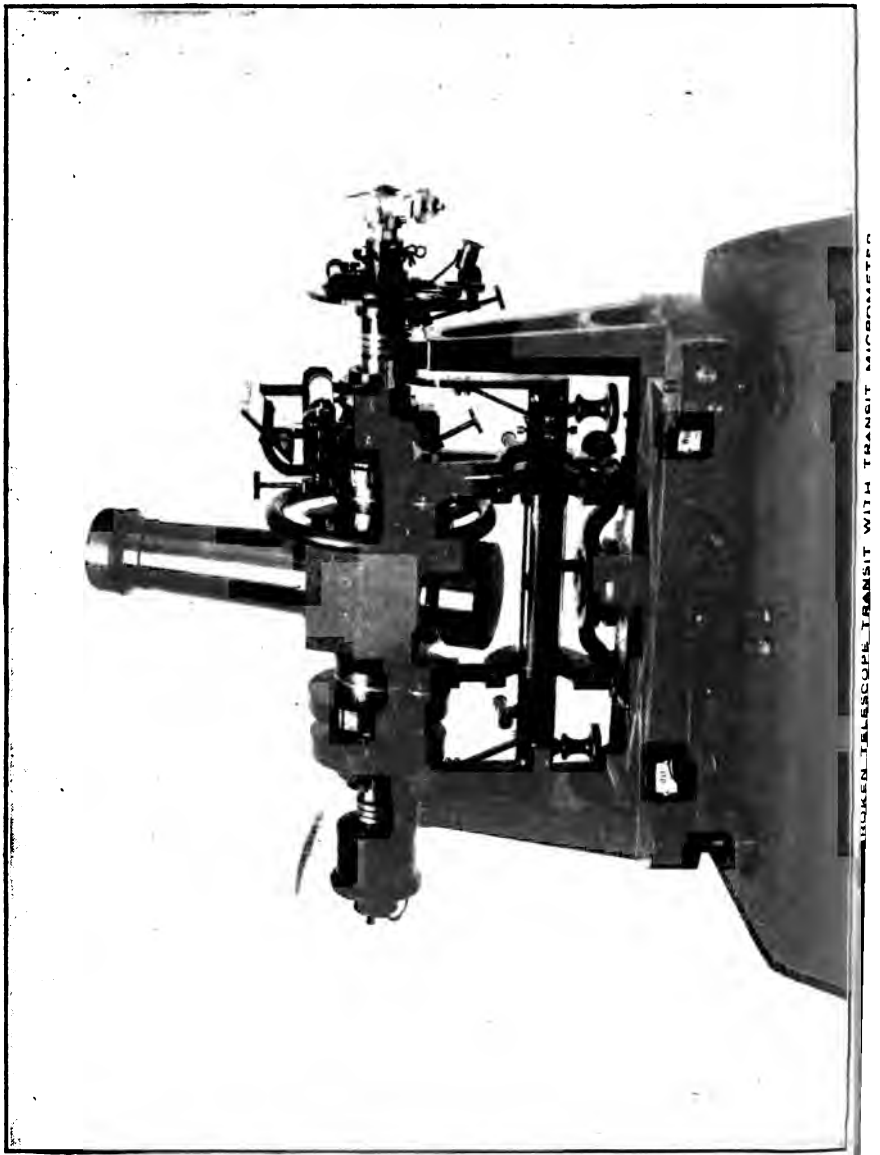
The most exact method of determining the difference of longitude is by means of the electric telegraph. In this method arbitrary breaks of an electric current in a wire joining the two places of observation are recorded on chronographs at the known and the unknown longitude stations. On each chronograph are recorded the seconds breaks of the local chronometer. The exact time of each of these chronometer breaks is known from observations on the stars made to determine the error of the chronometer. The time of each of the arbitrary breaks of the electric current can be scaled off very accurately from the chronograph sheet. This is done at each of the stations and the record of each observer is sent to the other. From the data thus obtained the difference of time between the two observatories can be computed with great accuracy.

In order that the transmission time through the electric system due to relays, etc., may be eliminated from the results, the breaks of the electric circuit are made partly at one station and partly at the other. When this has been done the mean of the recorded times of the breaks will be free from any error due to the transmission time. The arbitrary breaks of the electric current are made during an interval in the observations on the stars.

Usually two determinations of the local time are made in connection with longitude observations, one by observations on a set of five or six stars just before the arbitrary breaks are made and the other by a similar set just after the breaks. These two determinations furnish a rate of the chronometer. A statement in regard to the time determination is given under the heading "Time."

A primary or first-class determination of a difference of longitude by the Coast and Geodetic Survey depends on at least three nights of successful exchange of signals when time observations have been made at each end of the line. The probable error of such a determination is usually not greater than 0.02 second of time.

Much investigating has been done with the wireless telegraph in connection with the determination of longitude, but the process at



HUKEN TELESCOPE TRANSIT WITH TRANSIT MICROMETER

present is laborious and there is considerable uncertainty in the results, owing to the personal equation. It is possible, however, to receive the observations photographically and thus eliminate the personal equation of the observer receiving the radio signal. It is not unlikely that the determination of a longitude by radio may be of equal accuracy to that by wire but on this matter no exact data are yet available.

The longitude determinations by the Coast and Geodetic Survey are now made principally for the purpose of furnishing data by which the triangulation network of the country may be adjusted to the proper geographical position. A description of the methods used is contained in Special Publication No. 14 of this bureau entitled, "Determination of Time, Longitude, Latitude, and Azimuth." Figure 16 shows the longitude net of the United States and the stations which have been connected with it.

LATITUDE.

Latitude may be defined as the angular distance of an object or place north or south of the Equator. Hence, the latitude of a place becomes known when this angular distance has been determined.

The approximate determination of the latitude of a place may be made by the simple method of observing with a surveyor's transit or a sextant the altitude of the North Star as it passes the meridian. The North Star or Polaris is not exactly coincident with the extension of the axis of the earth to the celestial sphere. This star makes a circle approximately $2\frac{1}{4}°$ in diameter around the pole. It is readily seen that if we know the altitude of Polaris at the time it crosses the meridian below the pole, the latitude of the place is that altitude plus the polar distance of the star. This polar distance is 90° minus the declination of Polaris. Similarly, if we should observe the altitude of Polaris when it is on the meridian above the pole, the latitude of the place would be the altitude minus the polar distance. The latitude of a place may be observed also by determining the altitude of the sun as it crosses the meridian.

The declinations, or the angular distances of stars to the north or the south of the celestial equator, have been determined by years of observations at fixed observatories, and the results are contained in such publications as the American Ephemeris and Nautical Almanac, the Boss Catalogue of Stars, etc.

The method of determining the latitude of a place by observations on Polaris and on the sun is subject to considerable error due to what is called refraction or the bending of the rays of light coming to the earth from these bodies. The refraction is greatest near the horizon and gradually decreases to zero at the zenith or the point on the celestial sphere directly above the observer. It varies somewhat from hour to hour and day to day but is approximately the same for the same angle of elevation in all directions from the observer. This principle

has been made use of in what is called the Talcott method for the determination of the latitude of a place. In this method two stars are used, one to the south of the zenith and one to the north, that cross the meridian within a few minutes of each other. The zenith distances of the two stars selected seldom differ by as much as 20′. When using this method it is necessary to know within a few minutes the latitude of the place at which the observations are to be made in order that the proper stars may be selected. This latitude can be scaled from a map or can be determined roughly by an observation on Polaris or the sun, as mentioned above. Knowing the approximate latitude of the station and the local time the star, catalogues can be used to find a pair of stars that will meet the requirements of the Talcott method, that is, that will cross the meridian within a few minutes of each other and with zenith distances nearly the same.

The instrument used to make the observations is known as a zenith telescope and is shown in figure 10. After the instrument has been thoroughly adjusted in the manner that is common to astronomers and surveyors and the line of collimation or line of sight of the telescope has been placed almost exactly in the meridian, the telescope is set to such a position that the angle it makes with the zenith is about one-half the sum of the zenith distances of the two stars. At the eye end of the telescope of the instrument there is a micrometer with which is observed the difference in the zenith distances of the two stars. In the micrometer there is a wire fastened to a frame that moves on the micrometer screw. This wire is made to bisect the star as it crosses the meridian. The micrometer screw and head are then read to a small fraction of a second of arc. The telescope is then turned 180° on its vertical axis into position for the second star and the movable thread is made to bisect that star. The difference between the micrometer readings on the two stars gives the differences in their zenith distances. A very sensitive level tube is attached to the instrument and this is read immediately after the observations on the stars to obtain a value for the tilting of the vertical axis of the instrument. With the data obtained from the observations and with the known declinations of the stars, obtained from the star catalogues, the latitude of a station can be computed.

No observation can be made which is entirely free from error, but the effect of the errors of observation, though small, can be almost entirely eliminated by observing on a great number of stars. A primary latitude of the United States Coast and Geodetic Survey usually consists of observations on at least 12 pairs of stars and the error of the resulting latitude is usually less than 0.1 second, which corresponds to a distance of about 10 feet. This means that the astronomic latitude of a place on the earth's surface can be determined within this amount.

Descriptions of the instruments and their adjustments, and the methods of observing and of computing latitudes are given in Special Publication No. 14 of this Survey entitled, "Determination of Time,

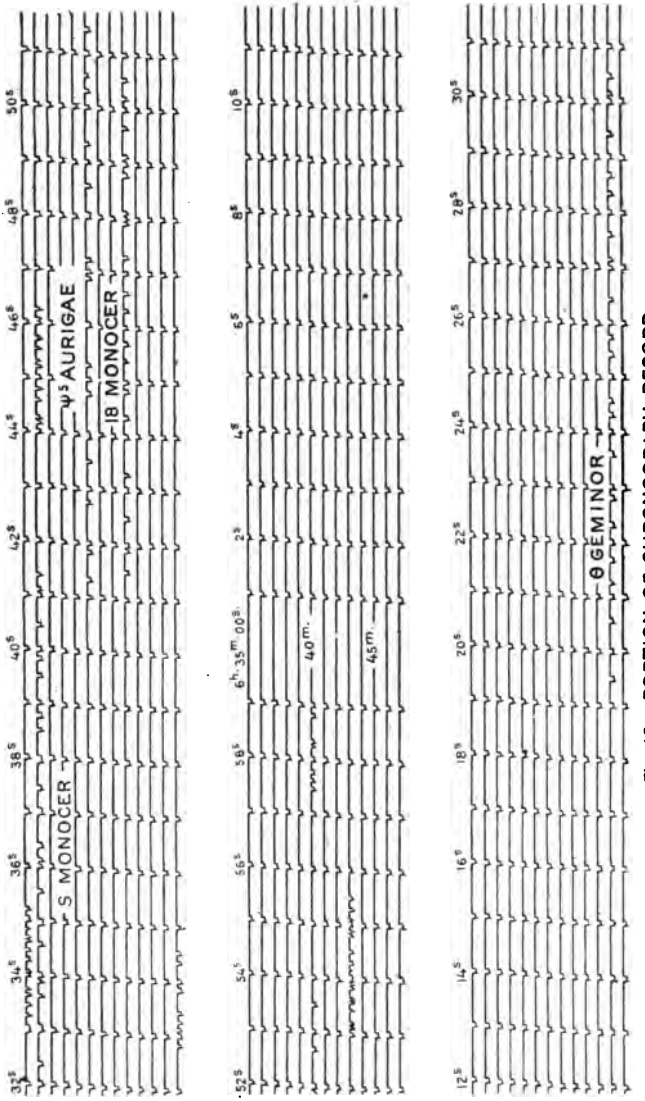


Fig. 15.—PORTION OF CHRONOGRAPH RECORD.

Longitude, Latitude, and Azimuth." and in "Directions for Magnetic Measurements." In the latter publication are given methods for obtaining approximate latitudes which are used where the latitude determination need not be of high accuracy.

AZIMUTH.

In all surveying and mapping operations it is necessary to know the true north or the direction of the meridian at various points covered by the survey or map.

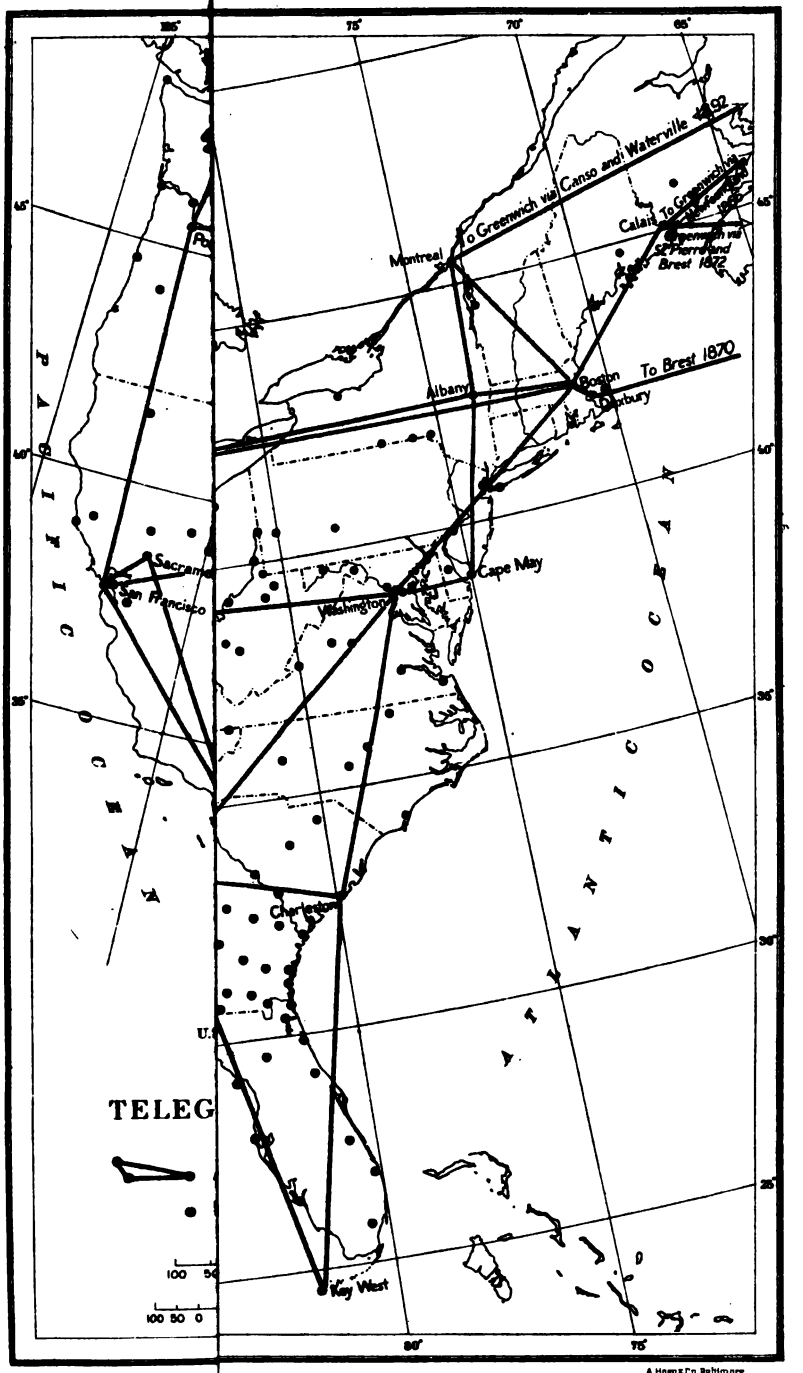
In the work of the Coast and Geodetic Survey the direction of the true meridian must be known in connection with the triangulation and magnetic observations made by the bureau. Astronomic azimuths are used to control the geodetic azimuths carried through triangulation. Before the astronomic zimuth can be used for this purpose it must be corrected for what is called the station error or deflection of the vertical at the point of observation. In magnetic work the direction of the true meridian must be known in order to determine the angle between that direction and the direction of the magnetic meridian indicated by the magnetic needle.

The direction of the true meridian is obtained by observations on the sun or on Polaris. Data that are necessary in order to compute the azimuth from the observations are, the approximate latitude of the place and the local time at which the observations are made and, in the case of the sun, the approximate longitude of the place of observation. The sun is changing materially in declination and right ascension from hour to hour while a star, on the other hand, changes only by an insignificant amount.

Observations on the sun are usually made with an ordinary surveyor's transit or theodolite and consist simply of pointing on the sun with the instrument, noting the time at which the observation is made and then pointing the instrument on some target or mark. The observations are repeated a number of times to eliminate the errors. The true bearing of the sun or the angle that the line from the observer to the sun makes with the true meridian, at the time of the observation, can be obtained from the American Ephemeris and Nautical Almanac. When the angle between the mark and the sun is combined with this true bearing of the sun, the true bearing of the line from the observer to the mark is obtained.

When observations are made on the sun for azimuth, the local time is usually obtained from a comparison of the chronometer or watch with the noon signal sent from the Naval Observatory over the telegraph wires of the country. A knowledge of the approximate local longitude is necessary. Where the telegraph office is not convenient to the point of observation, time is obtained by observations on the sun or stars with a vertical circle or a sextant, as is mentioned in the section of this article under the heading "Time."

The error of the result in the determination of azimuth by observations on the sun is usually about 20″ to 30″.


To Greenwich via Canso and Waterville 4492
Calais
To Greenwich via St Pierre and Brest 1872
Montreal
To Brest 1870
Albany
Boston
Duxbury
Cape May
Washington
Charleston
Key West
PACIFIC OCEAN
ATLANTIC OCEAN
TELEG
100 50 0
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A.Hoen & Co Baltimore.

Where a rough value only of the azimuth is needed, it is obtained by making observations on Polaris at the time this star is at eastern or western elongation. When it is in one of these positions the local time need be known only within a few minutes in order to obtain fair results in the azimuth. This is because Polaris is not changing rapidly in azimuth at that time.

When the most exact azimuths are required the observations are made on Polaris with a large theodolite which is also used in the measurement of horizontal angles. Before observations on Polaris are begun it is necessary to determine accurately the local sidereal time. For this purpose observations are made on several stars to the eastward and westward of the meridian with a special vertical circle. The time must be determined again after the completion of the observations on Polaris, in order to have a knowledge of the rate of the chronometer during the azimuth observations. The error of the determination of the clock correction is usually about one-half second.

For the azimuth observations, the instrument is first pointed on a mark which may be a distant triangulation station from which a signal light is shown. The position of the telescope with relation to the horizontal circle of the instrument is read with the micrometer microscopes, then the instrument is pointed on Polaris, and the time of pointing noted. The microscopes are again read, and the inclination of the horizontal axis of the telescope is determined by the reading of a very sensitive level. The telescope is then reversed in its supports or wyes, the inclination of the horizontal axis again determined, and a second observation on Polaris and another on the mark are made. This combination of observations completes a set and gives one determination of the azimuth of the mark. From 12 to 16 of these sets are made in order that it may be possible to eliminate the errors of observation.

The computations consist in determining the azimuth or bearing of Polaris with relation to the meridian at the time the observations were made. When this azimuth is combined with the angle between Polaris and the mark, there is obtained the bearing of the line between the observer and the mark. This is the result sought. The error of the determination of a first-grade azimuth is about one-third second. This is very small, as may be realized when we consider that 1 foot at a distance of 40 miles subtends an angle of 1″. Therefore, the azimuth may be considered as uncertain to the extent of about 4 inches in a distance of 40 miles.

After the true bearing of some line has been determined by azimuth observations, the exact meridian or true north and south line can be laid off on the ground by simply setting off an angle equal to the bearing of the observed line to the right or left of this line as the case may be.

There are descriptions of the methods used in determining astronomic azimuth given in Special Publication No. 14 and in Directions for Magnetic Measurements, United States Coast and Geodetic Survey.

TERRESTRIAL MAGNETISM.

The magnetic survey of the United States may be said to have had its beginning in 1843, when a plan for the reorganization of the survey of the coast was adopted which included a provision for making "all such magnetic observations as circumstances and the state of the annual appropriations may allow." Up to 1877 the work of the Coast Survey was confined almost entirely to the coast States and the magnetic observations were in most cases made in conjunction with some other branch of the Survey work. With the broadening of the field of the work of the Bureau as indicated by the change of title to "Coast and Geodetic Survey" (in 1878), observations were extended to the interior States, but up to 1899 the progress was slow. In that year an increase of the annual appropriation made it possible to undertake a systematic magnetic survey of the country and led to the formation of a separate division in the office to take charge of the work.

The early magnetic work of the Coast and Geodetic Survey developed in response to the demands of the navigator and the surveyor. The primary object of the survey of the coast of a country is to supply the mariner with all the information needed for the safe navigation of the adjacent waters. When no landmarks or heavenly bodies are visible, he must depend upon the mariner's compass for his guide. Unfortunately the compass needle does not, in general, point true north, nor is its direction at any particular place constant. In the United States, for example, the compass needle points 22° west of true north in northeastern Maine, and 25° east of true north in northwestern Washington. In Maine it now points as much as 8° more to the west than it did 150 years ago. It is evident, therefore, that a knowledge of the compass variation (magnetic declination) is indispensable to the navigator when using his compass.

With iron and steel ships the problem of the navigator is further complicated by the effect upon his compass of the component parts of the ship. The solution of this part of the problem requires a knowledge of the dip (inclination) and the intensity of the earth's magnetic field.

Nearly all of the early land surveys in the United States were made by compass and the boundaries in the deeds were defined by compass bearings. With the lapse of time and increase of land values, controversies arose as to the location of boundary lines which had not been marked or of which the markings had disappeared. In order to retrace the lines of a piece of land surveyed originally by compass,

the surveyor must know the change in the direction of the compass needle, that is, the change in the magnetic declination, in that particular locality between the date of the original survey and the resurvey. The Coast and Geodetic Survey has collected a large amount of data regarding the secular change of the magnetic declination in this country since the date of the earliest observations and has made a careful discussion of the collected material. As a result, it is in a position to furnish the best information available for the settlement of such disputes in regard to boundary lines.

In view of the difficulties experienced in retracing old compass surveys, accentuated as they were by inferior instruments and often by carelessness or lack of knowledge on the part of the early surveyor, it became important to guard against a similar condition as to present-day compass surveys by determining in detail the distribution of the magnetic declination throughout the country, as well as its change with lapse of time, at the same time providing local surveyors with meridian lines or other means of testing their compasses.

When the systematic magnetic survey of the country was undertaken in 1899, the following plan was adopted:

1. The determination of the three magnetic elements—declination, dip, and horizontal intensity—at places 30 to 40 miles apart on the average, distributed over the whole country, followed by a more detailed investigation of areas of local disturbance.

2. The reoccupation from time to time of a sufficient number of "repeat" stations to determine the secular change of the magnetic elements.

3. The operation of magnetic observatories for the control of the field observations, for a more detailed record of the variations of the earth's magnetism, and for the accumulation of the data needed for the study of the nature and cause of the phenomenon.

Following this general plan, the distribution of stations has been based largely upon the county subdivision of the States and observations have been made at all but about 150 of the county seats, thus making readily available the data needed by the county surveyors to test their compasses. In addition, a number of areas of marked local disturbance have been examined in more detail. Between 50 and 75 repeat stations have been occupied each year, the average interval between successive occupations being about five years.

To supplement the observations on land and extend our knowledge of the distribution of the earth's magnetism beyond the shore lines, some of the vessels of the Survey have been equipped with suitable instruments for determining the magnetic elements at sea, and valuable results have been secured in connection with the regular survey work of those vessels.

Magnetic observatories have been in operation at Cheltenham, Md., since 1901; Sitka, Alaska, and near Honolulu, Hawaii, since 1902; Vieques, P. R., since 1903; Baldwin, Kans., from 1901 to 1909; Tucson,

Ariz., since 1909; at which continuous photographic records of the fluctuations of the earth's magnetism have been secured. Seismographs are also in operation at each of these magnetic observatories for recording the earth tremors produced by earthquakes, thus supplying information regarding the condition of the interior of the earth as it affects the propagation of earthquake waves.

In addition to the work in the continental part of the United States, magnetic surveys have been made of Porto Rico, Hawaii, and the Philippine Islands, and many observations have been made in Alaska, principally along the coast and the Yukon River.

It is the policy of the Survey to publish the results of the magnetic observations as promptly as possible so that they may be available for general use by the public. They are published in various forms.

1. On every coast chart there are given for one or more positions the value of the compass variation for a specified year and the annual rate of change. Similar data for prominent points along the coast are given in the various Coast Pilots.

2. The results of the field observations, together with brief descriptions of the stations occupied, are published annually, formerly as an appendix to the Superintendent's annual report, but now as a separate publication.

3. About once in five years an isogonic chart is issued on which the distribution of the magnetic declination for a specified year is shown graphically by means of lines of equal magnetic declination. This chart is accompanied by secular-change tables showing the change of the magnetic declination since the earliest available observations at one or more places in each State. With the aid of these tables the surveyor can determine the change of declination for which he must make allowance when attempting to retrace the lines of an old survey.

4. About once in 10 years the accumulated results have been published collectively, together with corresponding reduced values for a specified year. These tables are accompanied by maps, on which the distribution of the declination, dip, horizontal intensity, vertical intensity, and total intensity are shown graphically by isomagnetic lines.

5. The observatory results are published biennially and include values of declination, horizontal intensity, and vertical intensity for each hour, maximum and minimum values for each day, daily means and hourly means for each month, tables showing the average diurnal variation of the magnetic elements and components for each month, reproductions of the magnetograms showing the more marked magnetic disturbances, and earthquake tabulations.

6. The publication entitled "Principal Facts of the Earth's Magnetism" gives a summary of the development of our knowledge of the subject and contains also directions for determining the true meridian with a simple instrumental outfit, together with tables to facilitate the work.

SEISMOLOGY.

In order to determine whether there is any relation between earthquakes and magnetic disturbances, seismographs have been operated at the five magnetic observatories of the U. S. Coast and Geodetic Survey at Cheltenham, Md., Vieques, P. R., Tucson, Ariz., Sitka, Alaska, and near Honolulu, Hawaii.

A seismograph consists essentially of a mass of metal of considerable inertia, suspended in such a way that movements of the earth's crust are communicated to it in only a very slight degree. A suitable recording device, fixed rigidly to the ground, registers any movement of the earth at the station relative to the suspended "steady mass."

An earthquake sets up vibrations in the earth's crust which are transmitted through, and along the surface of the earth for great distances, sometimes completely round the earth. From the observational data obtained from seismographs it is possible to determine the origin and time of occurrence of the earthquake and the rate of propagation and other characteristics of the resultant vibrations or waves. This information constitutes a valuable contribution to the development of the science of seismology and is useful also to the geophysicist in the solution of problems such as isostasy which involves a knowledge of the nature and properties of the crust and interior of the earth.

TOPOGRAPHY.

A topographic map is one on which the natural and artificial features of the country are represented in their proper geographic positions by conventional symbols.

The two most important symbols on maps, where they occur, are the "shore line," or boundary between land and water, and "contour lines," which are lines of equal elevation above a selected plane, such as the sea level. A contour is in fact a representation of what the shore line would be if the level of the water were to rise to the elevation indicated by that particular contour.

In order to show the undulations of the ground, contour lines are drawn for some constant vertical interval—20 feet, for instance. On large-scale maps they have superseded the representation of heights by hachures, or shade lines, which only picture the configuration of the country, without furnishing the means, as the contours do, of stating in terms of some linear unit the difference of elevation.

In reading a map one is able to tell the nature of the country from the various symbols—whether it is high or low, rugged or gently undulating—by the number and arrangement of the contours or hachures, and whether it is marshy or sandy, wooded or rocky, and so on.

A topographic map is particularly valuable for the study of the physical conditions relating to engineering projects in general, such as the preliminary location of railroads and highways, the problems relating to water supply, drainage, etc. It serves as a basis for directing military movements and planning military works of defense. Combined with hydrography, it forms a chart on which is shown the relation of land to water for purposes of navigation and the improvement of harbors and waterways.

Charting the coasts of the United States is the chief function of the Coast and Geodetic Survey, and topography is necessarily included as one of the important features of its work.

A topographic survey has for its object the collection of data for the construction of a topographic map. The character of the map in regard to accuracy, scale, and fullness of detail depends on the purpose which it is intended to serve. Military topographic sketches are frequently made by using a pocket compass, the stride of the observer or his horse serving to estimate the distance. More elaborate methods are used where greater accuracy is required and greater detail is desired.

Different topographic methods require the use of various instruments and may, for the purpose of description, be classed under four

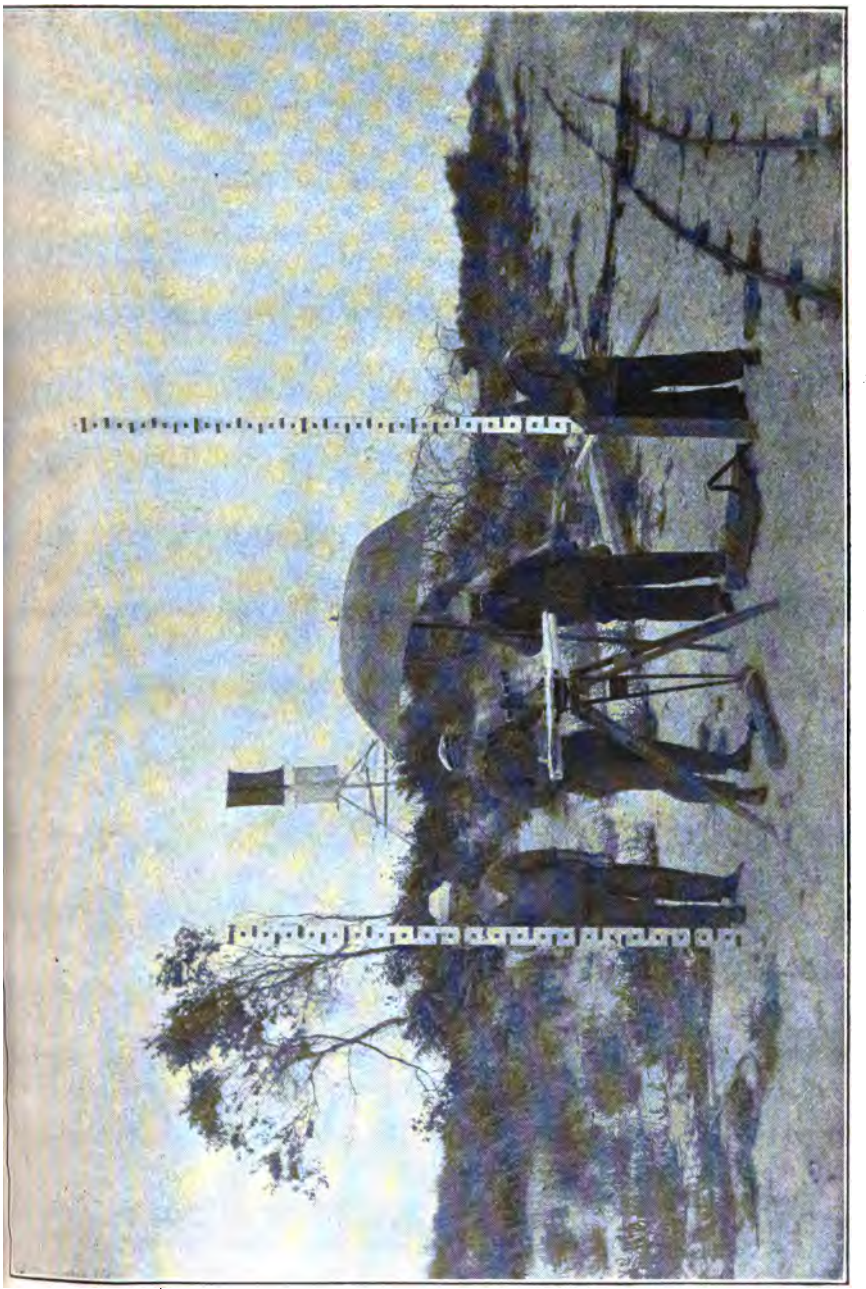


Fig. 17.—TOPOGRAPHIC FIELD PARTY AND EQUIPMENT.

heads, from the fact that each method is identified with some particular instrument or combination of instruments with which the principal part of the work is done.

1. *With a chain or steel tape and level, by what may be called the checkerboard system.*—The whole area is subdivided into rectangles by a system of distances measured with a chain or steel tape and marked by pegs whose elevations are determined with a level and rod. The positions and elevations of the pegs having been plotted, the contours are drawn on the plan with reference to them, and all other details are located by measurements from them. This method is best adapted for small areas where work of construction is shortly to follow the survey.

The topography of the ordnance survey of Great Britain was executed by traversing the country with a network of straight lines measured with a chain, the accuracy of the work being controlled by starting each line from one triangulation point and ending at another. Offsets were measured from the line wherever it was necessary to locate details. The elevations of a number of points on the ground were determined by the level, and the contours were sketched with reference to these after the rest of the details had been plotted. This is the simplest of all instrumental methods in the field, but it is not efficient where there is little detail or where the ground is unsuitable for chaining.

2. *With transit and stadia.*—This method is a development of the preceding one. The country is likewise traversed by lines, but instead of chaining the distances are read through the telescope of the transit on the stadia rod held at any desired point. The level is also dispensed with, as the height of any point can be determined by computation when its distance is known and the vertical angle to it is observed. A vertical circle is attached to the transit for this purpose. All the names of the objects sighted upon, as well as the distances and angles to them, are entered in a notebook, together with sketches of the locality, to assist the draftsman to interpret the notes.

3. *With the photographic camera.*—(*a*) Optical axis of camera horizontal.—Surveys can be made with an ordinary landscape camera, but there are many advantages in having one especially designed for the purpose. The essential feature of this method consists in occupying a sufficient number of camera stations to fully cover the territory to be mapped, so that every topographic detail of importance may be photographed from at least two stations. This is one of the most rapid of all instrumental methods in the field, since a great deal of topographic material can be gathered photographically in a short time. It has the serious drawback that for areas abounding in detail the plotting becomes overwhelming. It has been found most useful in mapping rugged mountainous regions with characteristic features which can be identified in photographs taken from two or more different points of view.

(*b*) Optical axis of camera vertical or at known angle.—Airplane photographs were used to a very large extent during the World War in

locating military features within the area occupied by the enemy. The experience then gained is being utilized in developing methods and apparatus for topographic surveys. At present it is not certain to what extent they will supersede the usual methods. The most promising field for surveying and mapping from an airplane is over flat country, or country with low relief, and in revision surveys. The changing features are shore lines, woods, roads, and villages, and these features can be readily placed on the old map by fitting in the new features shown on the photograph to the unchanged features shown both on the old map and the photograph.

By the foregoing methods the map is constructed in the office; by the following method its construction is coincident with the field work.

4. *With the plane table and stadia.*—This is the principal method used for topographic work by the Coast and Geodetic Survey. For this purpose the plane table is a universal instrument. All the necessary operations for producing a map are executed with it in the field from the country as a model. Other instruments may at times be employed as auxiliaries, but in general it alone fulfills all requirements. Owing to the rapidity with which results are obtained by the method of graphic triangulation, and the facility the plane table affords the topographer for determining his position at an unknown point by the graphic solution of the three-point problem, and in the effective use of the stadia, it is an instrument peculiarly fitted for delineating coast topography, which includes such features as outlying islands and ledges, inaccessible rocky bluffs, and large marsh areas intersected by numerous streams. (For further details see Plane Table Manual, Report for 1905, Appendix 7.)

HYDROGRAPHY.

The object of the hydrographic surveying here considered is to determine the depth of the water and to outline the channels, banks, and shoals, and to locate all dangers and aids to navigation necessary in the construction of charts.

Physical hydrography relating to tides and currents is elsewhere described.

To the navigator the results of the hydrographic work are the most important features represented on a chart. The first need of the hydrographer in making his survey is a projection or outline map showing the meridians and parallels, the shore line and land features visible from the water, prominent objects, spires, houses, artificial signals, capes, headlands, and outlying rocks and islands visible from the shore.

The two branches of surveying on which hydrography is most dependent, and which it is most convenient to have precede it, and on which its accuracy largely depends, are the triangulation and the topography. These subjects are described elsewhere in this pamphlet. The triangulation fixes the position of the trigonometric points on land by means of which the location of the soundings is determined. The topography provides the delineation of the shore, locates the rocks that show above water, and the limits of dry shores and banks. It is also essential for the navigator to know the character of the shores bordering on the waters which he traverses; their prominent and characteristic features are an important guide in navigating his vessel. These data are placed in their proper relative positions on the outline map above mentioned. The scale of this outline map, or projection, will depend upon the minuteness with which the submerged features are to be mapped, and this in turn will largely depend upon the character of the area and its importance to navigation or other commercial purpose. A scale of 1/10,000 (which means that 10,000 feet in nature are represented by 1 foot on the projection) is well adapted for the survey of most harbors. The points determined by triangulation are plotted on the projection in their proper geographic positions. These points consist of prominent objects, such as church spires, chimneys, conspicuous rocks or trees, and specially built signals, all of which are of a suitable character to observe upon from a boat or vessel while sounding.

When a sufficient number of these signals or other objects have been located and a tide gauge or tide staff has been erected at some suitable

Fig. 18.—DETERMINING POSITION ON SOUNDING LINE (PHILIPPINE ISLANDS).

point in the vicinity of the work, the next step in the hydrographic survey is making the soundings for the depth of water. Power launches and ships are now more often used than rowboats in running sounding lines. The lines of soundings are run in accordance with such a scheme as will best develop the contour of the bottom and its characteristic features; generally a rectangular system of lines is used, and where the two systems of lines cross each other the soundings must agree within prescribed limits varying with the depth of water. When beginning a line of soundings, two observers, with sextant in hand, the recorder, with a watch or clock and record book, and the leadsman, with his lead line, take their respective positions. The officer in charge of the sounding party directs the recorder to make a note, say, as follows: "Line begins at angle No. 1, about 20 meters from shore, south of Flecks Point; compass course east." The observers measure with their sextants the two angles between three shore signals and read the angles measured; the leadsman gets a cast of the lead and calls out the depth of water in feet or fathoms and feet, and the recorder records all these with the time the boat begins to move. The boat does not stop again until the end of the line is reached. The position of the boat is determined by the observation of pairs of angles at equal intervals of time (two to four minutes usually), or when there is a change in the direction of the line, or a change of speed of the boat, or sudden change in depth of water, and at the end of the line. Where the depths are changing rapidly the soundings are taken by the leadsman as frequently as possible, and the time of each sounding may be noted to seconds; but where the bottom is comparatively level the soundings are preferably taken at equal intervals of time. The pairs of angles taken for position of the sounding boat are plotted on the projection or outline map by means of a three-arm protractor; thus each sounding is laid down in its proper position.

When practicable the lines of soundings are run on ranges; that is, with the boat in the same straight line with two fixed objects on shore.

While the boat has been running the lines of soundings, the water has not remained at the same level owing to the rise or fall of the tide, and, therefore, the tides must be observed by means of a staff or self-registering tide gauge while the sounding is in progress, so that the depths can be reduced to a common plane of reference. Each sounding must therefore be corrected for the stage of the tide at the time it was taken. The plane of reference adopted by the Survey for the charts of the Atlantic and Gulf coats is that of "mean low water,"[1] which is, roughly speaking, the mean reading of all the low waters observed on the tide staff for as long a period as practicable, but usually not less than one lunar month. The reading of mean low water on the tide

[1] Because of a difference in the type of tides upon the Pacific coasts of the United States and Alaska, Hawaii, and the Philippines, all soundings are reduced to the plane of mean lower low water with the following exception: For Wrangell Strait it is 3 feet below lower low water.

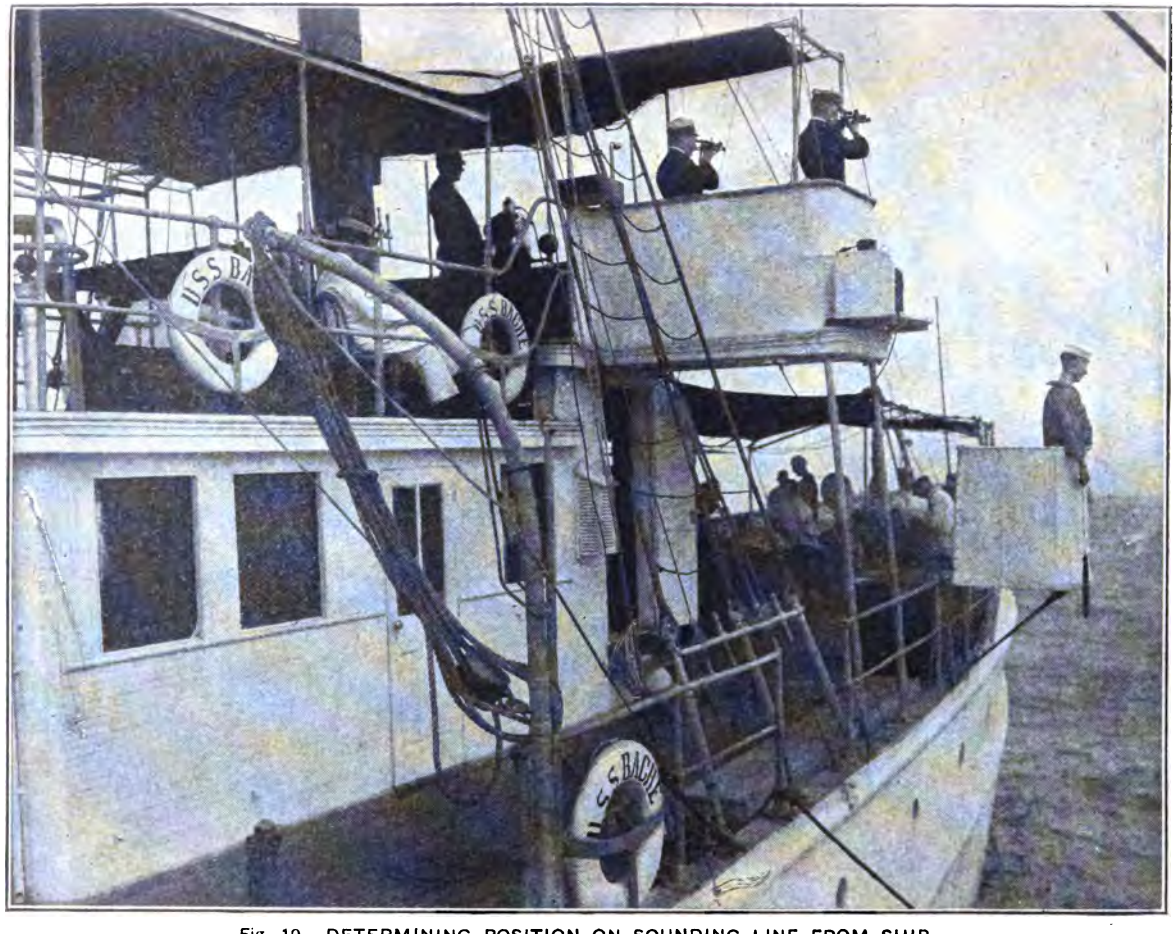


Fig. 19.—DETERMINING POSITION ON SOUNDING LINE FROM SHIP.

staff being known, and observations of the height of the tide having been made at sufficiently frequent intervals while the soundings were in progress, it is easy to apply the tidal corrections. In order to preserve the plane of reference permanent tidal bench marks are established on shore and the plane of reference is referred to them by leveling. Descriptions of these bench marks are preserved in the archives of the office.

In deep-sea sounding offshore, it is not necessary to apply the tidal reduction to the soundings.

The successive positions of the sounding boat being plotted, and the number and time intervals of the soundings being shown in the record, it becomes an easy matter to space the soundings accurately between the positions. The result is practically the same as though the boat's position had been instrumentally ascertained at each sounding.

Up to depths of about 20 fathoms the soundings can readily be made by the hand line. For soundings between 20 and 35 fathoms a satisfactory and often used method is that of dropping the lead near the bow and reading the depth as the lead comes vertical under the leadsman stationed on a platform aft. Various methods are used for carrying the lead forward and automatically releasing it. At greater depths, including deep-sea work, the vessel is stopped while the sounding is made and a sounding machine used.

The sounding machine may be briefly described as a reel or drum filled with stranded or piano wire, suitably mounted and operated either by hand or a small reeling engine, the essential purpose of the engine being to reel in the wire after the sounding is made. Attached to the wire is a heavy sinker, and the depth of water is obtained by a measuring reel over which the wire runs in taking the sounding.

When sounding in the deep offshore waters, piano wire is used on the drum of the sounding machine, and a spherical or pear-shaped shot weighing about 60 pounds is used as a sinker and is attached to the wire by a device which automatically detaches it on reaching the bottom. The wire is then reeled in by means of the reeling engine and a new sinker attached for the next sounding. The depth of water is measured by noting the length of wire run out, and, as a check, this is again noted in reeling in. In addition to ascertaining the depth of the ocean, a mechanical device is also attached to the end of the sounding wire which enables a specimen of the materials of the ocean bottom to be secured and brought up in deep-sea sounding. Besides this, specially devised thermometers and water bottles are attached to the sounding wire in such manner as to secure the temperature and specimens of sea water at any desired distance below the surface of the sea.

While the vessel remains in sight of land the method of determining position in running the sounding line is similar to that explained above for sounding boats and launches in inshore and harbor hydrog-

raphy, but when out of sight of land the position is obtained by astronomic observations and by precise dead reckoning.

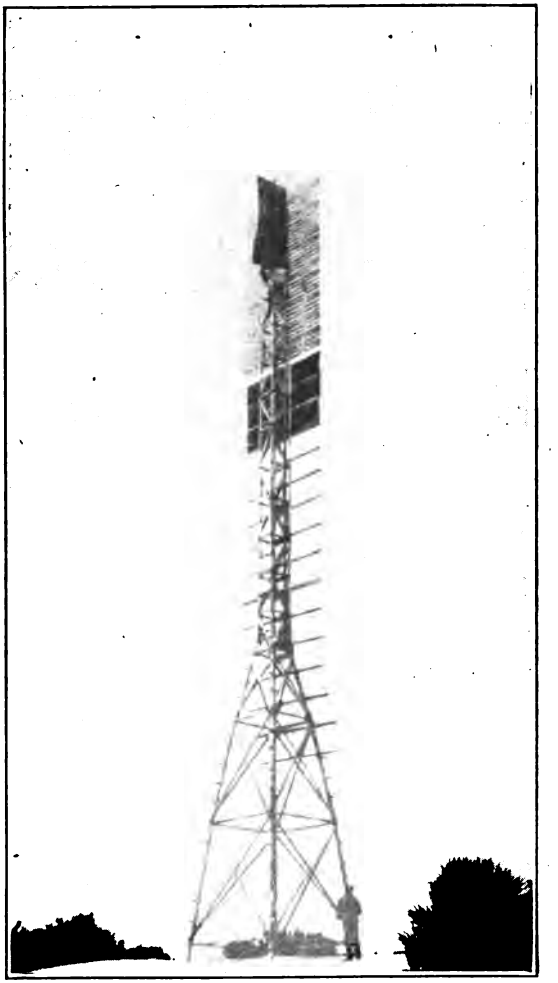


Fig. 20.—TYPE OF SIGNAL USED IN OFFSHORE HYDROGRAPHY.

A method of location of offshore sounding lines by dead reckoning more exact than that employed in navigation has been developed and employed since 1915. The finally adjusted positions of the sounding vessel is so much more exact than ordinarily obtained by dead reckoning that this class of hydrographic work may properly be termed "precise dead-reckoning hydrography." Locations by this method are used

offshore to the 100-fathom curve on the Atlantic coast and to the 1,000-fathom curve on the Pacific coast. For work farther offshore positions by astronomic observations with sextant are considered sufficiently accurate.

The combination of the two classes of work—that is, fixing positions by observing angles on fixed terrestrial objects and by precise dead reckoning—has been found to be best from a standpoint of economy, the inshore work being done during daylight hours when observations on signals are necessary and the precise dead-reckoning work at night over areas just offshore from the daylight work, and out of sight of fixed objects.

Tall signals, from 100 to 125 feet high, are built along the coast about 5 miles apart. (See fig. 20, p. 56.) These are accurately located by triangulation and plotted on the projection or chart on which the sounding work is to be plotted.

These signals along our low Atlantic coast line are visible from the bridge of the Survey steamer for about 8 or 9 miles offshore. About 3 miles outside this line of visibility another line of signals about 30 feet high are established. These are floating signals made by building a superstructure of angle-iron and wire mosquito-net targets on top of a tall-type can buoy. (See fig. 21.) The buoys are located by lines of direction with sextants from the bridge of the Survey vessel anchored at different positions just within the zone of visibility of the tall shore signals and located by angles observed upon them.

While sounding over the area from the shore out to the offshore lines of buoys and about 3 miles beyond them the vessel is located at intervals (two to five minutes) in a manner similar to that already explained for small-boat work, observing on three shore signals until beyond their range of visibility and then employing angles to three of the offshore buoy signals. About sundown the Survey vessel ceases this class of the work and steams over to one of the offshore buoy signals, where she anchors to obtain observations of the strength and direction of the wind and the set and drift of the current.

The sounding line is then started, the vessel heading straight offshore on a line laid down in the general system of development. At the end of two hours the vessel is again anchored and observations made for velocity and direction of wind and current. The course on which the vessel headed for that period of two hours is then corrected by an amount equal to the resultant of the forces of the current and wind as observed at the two anchorages. The line is then continued as far offshore as desired and a return made to the line of offshore buoys, stopping every two hours for current and wind observations. The vessel anchors within the zone of visibility of the offshore buoy signals about daybreak and angles are then observed on three of the buoys for an absolute fix. The closure—that is, the difference between the position determined by these angles and the one brought forward during the night by precise dead reckoning—is adjusted back throughout the

line, each leg of the course (two-hour run) receiving its proportion of the closing error.

The Survey vessel then continues the inshore daywork.

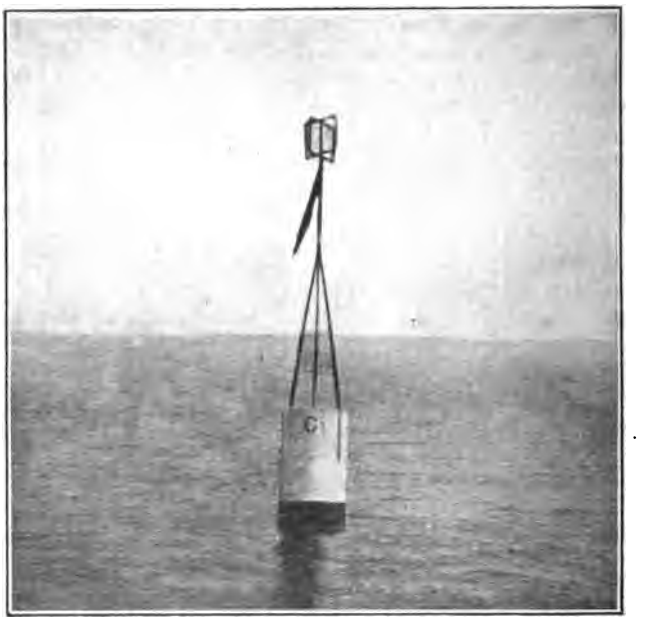


Fig. 21.—TYPE OF FLOATING SIGNAL USED IN OFF-SHORE HYDROGRAPHY.

The accuracy attainable by use of this method may be shown by citing an instance of a line run by one of our Survey vessels from the Florida coast out to the Gulf Stream and return, a distance of 105 miles for the round trip. In addition to the bihourly anchorages, for observation of the coastal tidal currents, observations were made at the 100-fathom curve and a current of 3¾ knots (sea miles per hour) was observed in the Gulf Stream. Upon return to the line of buoy signals the position of the vessel as determined by angles on three buoys differed by only 900 yards from the position as determined by this precise dead reckoning. Had the vessel made this run without taking into account the effect of winds and currents as outlined above the dead-reckoning position would have shown the vessel 25 miles down the coast.

Hydrographic surveys with the lead line while developing the slopes of the bottom do not with certainty reveal all of the hidden dangers to navigation that lie in the pathways of ships. In regions like the coast of Maine and in Alaska, where there are isolated rocks and ledges on the bottom, or in the tropical regions fringed with coral reefs and dotted with coral heads, the work must be supplemented by

special examinations with special appliances. Owing to the extension of commerce and its increasing demands, bringing in use ever larger and deeper-draft vessels, much special examination is now required. To meet these requirements and in order to be certain that an area is free of all obstruction to navigation to a specified depth the water area is swept over by an appliance known as a wire drag, which is essentially a suitable wire of any desired length (up to 15,000 feet long, so far used), supported at intervals by specially designed buoys so arranged that the wire can be maintained at any required depth irrespective of the changes in the stage of the tide. This apparatus is towed through the water by two power boats, and if no obstruction is encountered it is certain that no dangers exist at a less depth of water than that at which the drag was set.

The use of the wire drag has now become such a necessity in a finished hydrographic survey in areas where there is a possibility of isolated rocks that a brief account of its construction and use is of interest. Sweeps or drags were used long ago for locating pinnacle rocks or small ledges whose positions were approximately known, but the improvement of such apparatus so as to be an economic instrument for general application in searching out obstructions to navigation that may exist in any area is of recent development and as now used it has reached a high degree of efficiency. As described in Coast and Geodetic Survey Special Publication No. 56, the drag consists of a horizontal member known as the bottom wire, which is composed of a number of sections or units of double-galvanized, seven-strand, steel wire, one-eighth inch in diameter, supported at intervals by uprights, made of flexible wire cable, with suitable buoys and sinkers, and at intermediate points by hollow metal floats. At each end of the drag and at each section the buoys are large enough so as to rest on their bilge flanges when at rest with the large sinker attached. The intermediate buoys are smaller and when at rest project about 6 inches out of the water. Tow lines from the power boats are attached to the large buoys and sinkers in such a way as to permit changing the depth of the drag while in use.

One of the best features of the wire drag is the rapidity with which an area can be examined. The length of drag now commonly used is 3,000 feet or over, except when used in channels of less width than this. The average speed of the drag through the water is about a mile and a half per hour, and the area that can be covered in a day depends largely upon local conditions, such as natural or artificial obstructions. As many as 15 shoal spots have been found in a single day's work.

After a shoal spot or other obstruction is located by the drag, the drag is released and proceeds with its work, while a separate party develops the shoal area to ascertain the extent and character of the area and the least depth of water over it.

For handling the drag and towing it when in use it has been found that large launches or power boats are essential, boats of 80 horsepower and 14 foot beam now being employed.

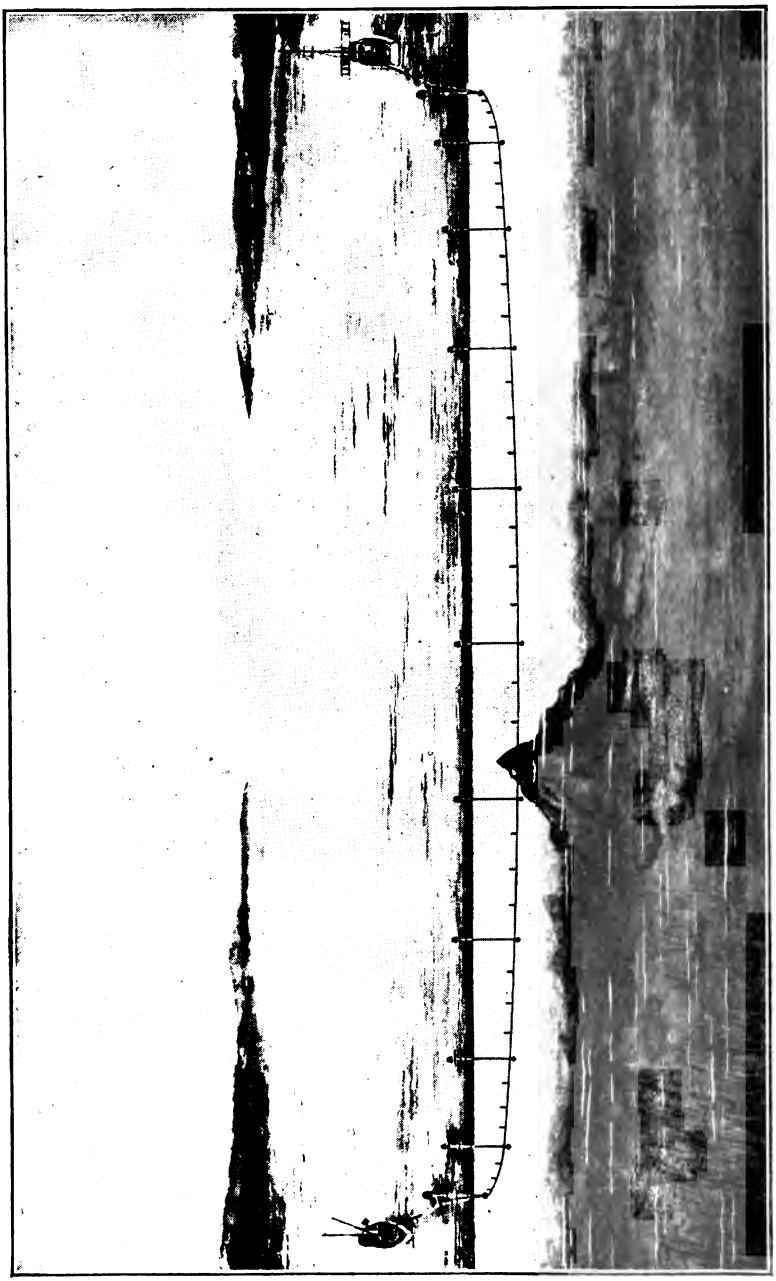


Fig. 22.—WIRE DRAG.

The drag is removed from the water at the close of each day's work. This operation requires about 25 minutes for a drag 5,000 feet long, and the time required for other lengths is proportional to this. It requires about the same length of time to set out the drag ready for work. Changes in the depth of the drag, made necessary by changes in the stages of the tide, are made by separate launch parties, while the drag is going ahead with its work.

Great accuracy is required of the hydrographer, even where the water is so deep that there is no possible danger of the largest ship afloat touching bottom, because the hydrography shown on a mariner's chart has a twofold object: First, to point out to the navigator the invisible dangers which he must avoid; and second, to reveal the configuration of the bottom and also its physical characteristics so truly that by the use of his sounding appliances he may fix his position in relation to those dangers, or when offshore or the coast line is invisible determine his distance from land. The results of the hydrographic work shown on the charts are of prime importance to the navigator. The manner of chart publication and issue is described in another part of this pamphlet.

For details of the theory and practice of hydrographic surveying the reader is referred to "General Instructions for Field Work of the Coast and Geodetic Survey" and "Wharton's Hydrographical Surveying."

TIDES AND CURRENTS.

The sea is never still; even in the calmest weather its surface is subject to the alternate elevation and depression brought about by the tides. This alternate rising and falling of the level of the sea, which at most places occurs twice daily, remained an unexplained phenomenon until the latter half of the seventeenth century. Newton then formulated the law of gravitation, and showed that the tides were one of its necessary consequences, due to the attraction of the sun and moon upon the rotating earth.

As explained previously under "Hydrography," the tides are of immediate importance in all hydrographic surveying. Whenever depths are sounded, it is necessary to know the state of the tide in order that the soundings may be reduced to a common plane of reference.

The times and heights of the tide are considerably influenced by terrestrial agencies, such as river discharge, winds, and variations in atmospheric pressure. As a consequence, any plane of reference, such as for instance that of mean low water, which is determined from a short series of observations at one time, may differ considerably from the low-water plane determined at another time. It is therefore necessary to have long series of observations at a number of important points which are representative of the tidal conditions of large areas. Short series of observations at any place may then be corrected by comparison with simultaneous observations at the above-mentioned representative points.

Where tidal observations are to cover but a short period of time, a simple tide staff is used. This is a plain board, graduated in feet and tenths, about 5 inches wide, 1 inch thick, and of a length greater than the extreme fluctuation of the water surface in the locality in which it is to be used. It is secured in a vertical position with its lowest graduation below any probable low water, and the observer notes the level of the water upon this staff at definite intervals, usually quarter-hourly, half-hourly, or hourly.

If a long series of tidal observations is desired, use is made of the self-registering or automatic tide gauge. This is a comparatively simple apparatus the essential parts of which consist of a clock that moves a sheet of paper forward uniformly, and a float that rests on the water and rises and falls with the tide. This float, by suitable means, is made to move a pencil up and down the paper, so that the combination of the motions of the paper and pencil automatically produces a curve from which the height of the tide at any desired time may be obtained.

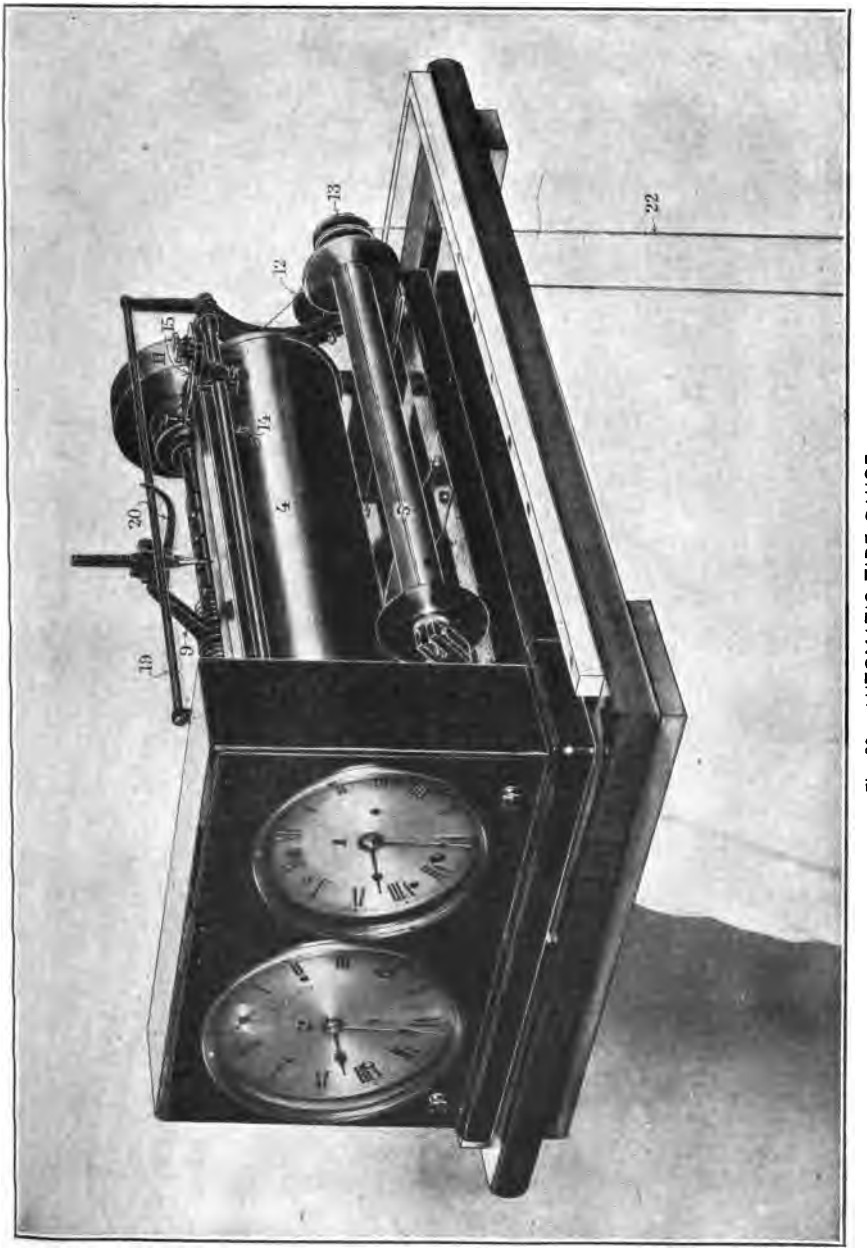


Fig. 23.—AUTOMATIC TIDE GAUGE.

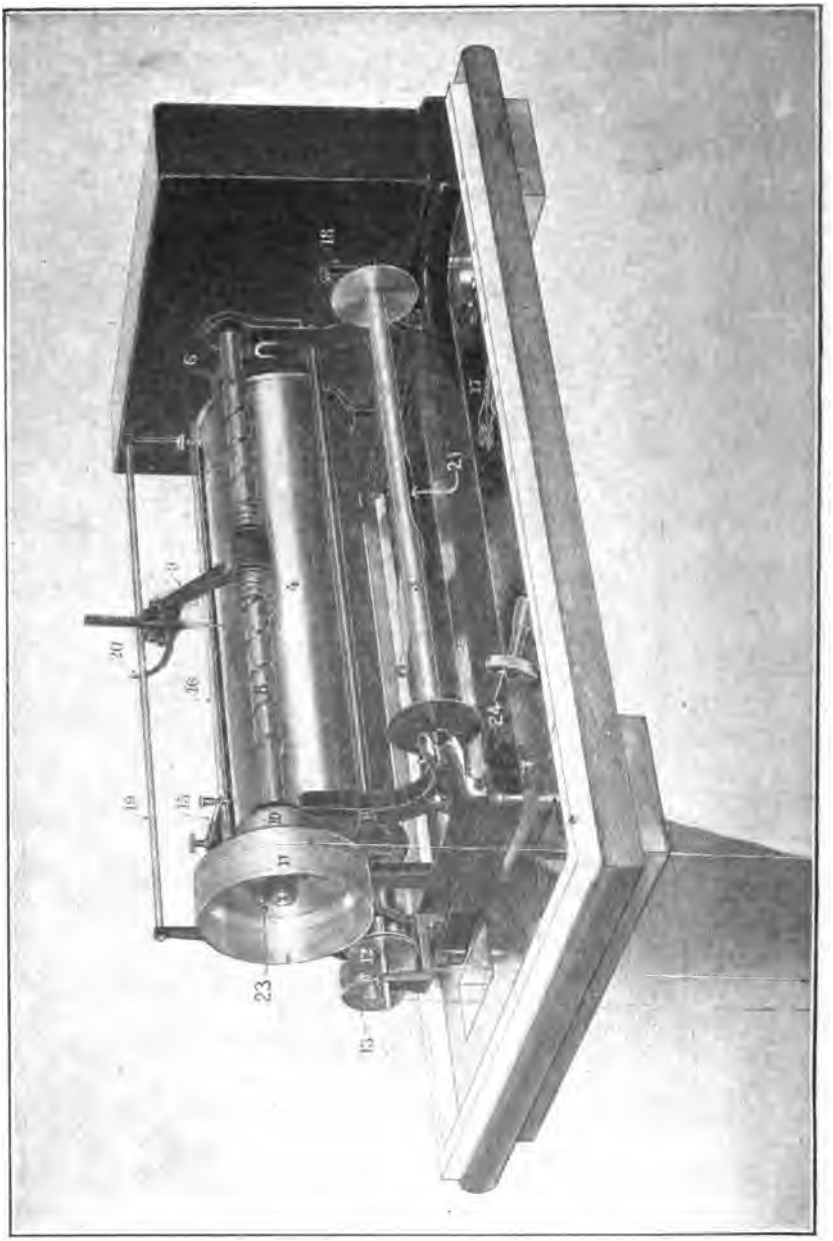


Fig. 24.—AUTOMATIC TIDE GAUGE (ANOTHER VIEW).

Long series of tidal observations, besides furnishing data necessary in the correction of a short series, have a number of other important uses. They are the only means for securing an accurate determination of the important plane of mean sea level, which is the datum used in precise leveling and in other engineering and scientific work. They also furnish data used in the study of the phenomena associated with earthquakes and storms. They furnish, too, the basic material for the study of the complex phenomena of the tides, many elements of which require a number of years for their evaluation.

All along the coast wherever tides are observed, the Coast and Geodetic Survey establishes tidal bench marks, the elevations of which, with reference to the planes of local high water, mean sea level, and low water, are determined. These bench marks then furnish for local use accurate data regarding the various planes of reference made use of by the engineer in the construction of wharves, docks, and other works of harbor improvement and coast protection.

With the advent of the deep-draft vessels of modern commerce, the tides have become of considerable importance in navigation; for the state of the tide determines when certain harbors may be entered, when bars may be safely crossed, and when short cuts over shoal places may be attempted. To aid the navigator, the Coast and Geodetic Survey has for a number of years published in advance, annually, tide tables giving for every day of the year the times and heights of high and low water for the more important ports of the world. By means of tidal differences given in these tide tables, the mariner may also obtain the tides for a large number of other ports in all parts of the world.

The earlier tide tables contained only a small number of ports for which full daily predictions were given. This was due to the fact that the computing of the predictions involved a great deal of laborious numerical work. Moreover, the results attained, while sufficiently accurate for practical purposes, were only approximately correct. Since 1882, however, the predictions have been made by the use of an ingenious machine known as the tide predictor. After this machine has been adjusted to make predictions for a particular port, the turning of a crank moves a system of pointers over dials which show accurately the time and height of high and low water for each successive day of the year at the port for which it is adjusted.

The tide-predicting machine first used by this Survey was the invention of William Ferrel, and was based upon his tidal work in the Survey. In 1910 this was replaced by an improved machine of a different type designed and constructed in the office of the Coast and Geodetic Survey. This new machine, which combines the best features of the tide-predicting machines invented by Lord Kelvin and William Ferrel, shows the time and height of high and low water, the height of the tide at any time, and also traces a curve of the tide. (See fig. 27.)

Due largely to the efficiency of the tide-predicting machine, the General Tide Tables issued annually in advance by the Coast and Geodetic Survey now give the predicted times and heights of high and low water for every day of the year for 81 of the principal ports of the world. They also give tidal differences which enable the mariner to obtain the tides for some 3,500 other ports in all parts of the world.

While the tides are due to the disturbing forces of the sun and moon, they are very greatly modified by terrestrial features. As a consequence, the tides present striking differences not only in time of occurrence and in range but also in type. Thus along the Atlantic coast of the United States the tide is almost wholly semidiurnal; that is, there are two high and two low waters each day and the afternoon tides are quite similar to the morning tides. On the Pacific coast, however, the type of tide is largely diurnal; that is, the afternoon tides are quite unlike the morning tides and on occasion there is but one high water and one low water in a day.

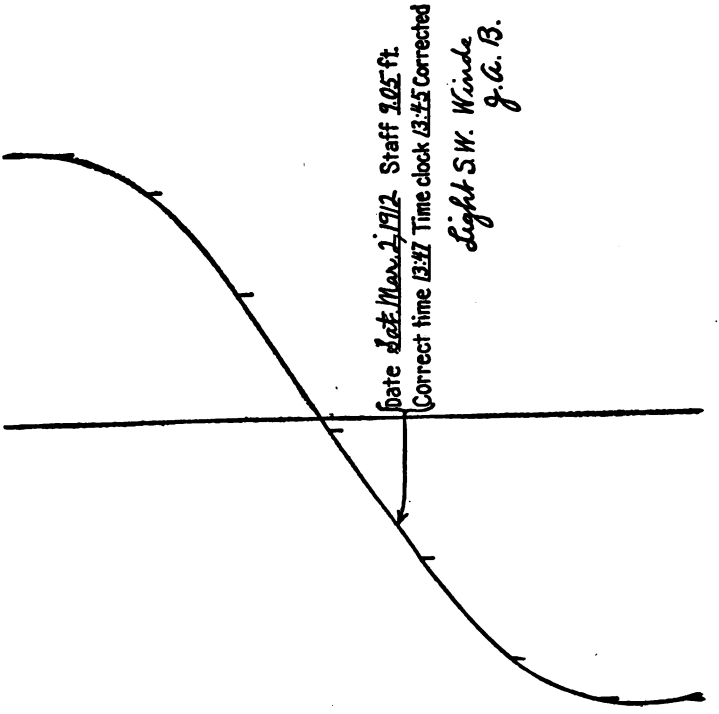


Fig. 25.—PORTION OF TIDE-GAUGE RECORD.

Even with the same type of tide we find great differences in range. In the upper part of the Bay of Fundy the tide rises, in the six hours from low water to high water, a vertical distance of more than 40 feet.

During the same interval the tide at Nantucket Island shows a range of but little more than 1 foot.

The tides, then, are local phenomena, and in order to predict the tide at any given place it is necessary to have tidal observations made at that place. These observations, which must extend over a period varying from one month to a year or more, are then subjected to the mathematical treatment known as the harmonic analysis. By this analysis the tide wave is resolved into a number of simple waves, each one specified by two numbers called, respectively, the amplitude and epoch of the wave. The amplitudes and epochs of all the different waves for each port are called the tidal constants for that port and are the elements entered into the tide-predicting machine for the purposes of predicting the tide, for any future time, at that port.

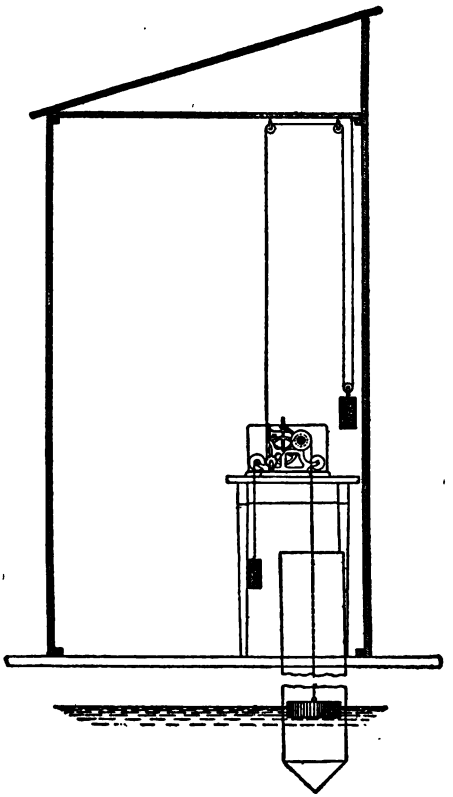


Fig. 26.—SECTIONAL VIEW OF AUTOMATIC TIDE-GAUGE STATION.

Currents have always been a factor of importance in navigation. In thick weather when the navigator is unable to determine the position

of his ship by reference to terrestrial or celestial objects, it becomes highly important that he know the velocity and direction of the currents to which his vessel may be subject. Also, where swift and dangerous tidal currents exist, the mariner must know the time of occurrence of slack water when such places may be safely crossed.

While the study of currents is intimately associated with that of the tides, it presents even more complex features. The tide over large areas shows considerable uniformity in time and in range, but the currents within the same region will present striking differences in time, in direction, and in velocity. The investigation of currents is therefore recognized as an important branch of the work of the Survey.

In the observation of currents, either a current meter or a simple current pole is used. The meter is of the bucket type with a telephone receiver, which permits the number of revolutions to be recorded. The current pole generally used is 15 feet long, weighted at one end so as to float 1 foot out of water. The log line attached to the pole is graduated so that the velocity of the current may be read off immediately when run out for a given interval, usually 28, 30, or 60 seconds.

For the purpose of aiding the navigator, there is published in the tide tables the predicted times of slack water for every day of the year at nine important stations where the velocity of the current is considerable. Current differences are given by means of which the mariner may determine the time of the current at more than 200 other places. Current diagrams showing the condition of the current with reference to the time of tide for seven localities are also included.

The tidal currents found in the inland waters and close inshore along the coast are of the reversing type; that is, the flood during its entire period runs in one direction, and the ebb, during its period, in the opposite direction. Some distance offshore, however, the tidal currents become more complex. Instead of flowing in the same general direction during the flood and in the opposite direction during the ebb, we find the current changing its direction continually. Instead of simply reversing in direction from flood to ebb, the offshore tidal currents are rotary in character.

Because of its semidiurnal character, we find this change of direction in the offshore tidal currents of the Atlantic coast to be at the rate of nearly 30° per hour. In other words, twice in each tidal day the direction of the current changes clockwise to every point of the compass. On the Pacific coast the offshore currents change in direction at a rate varying between 15° and 30° per hour.

Tidal currents, because of their periodic character may, like the tides, be predicted years in advance. Existing with these tidal currents and at times completely masking them we find the so-called nontidal currents which are due to river discharge, prevailing winds, differences in density of sea water, and other causes. Offshore these currents are frequently of far greater importance to the navigator than the tidal currents. Like the causes bringing them about, these nontidal cur-

rents show no periodicity. They do, however, show fluctuations corresponding to the seasonal variations in their causes. The Coast and Geodetic Survey has, therefore, undertaken the study of nontidal currents with a view to correlating them with the meteorologic conditions.

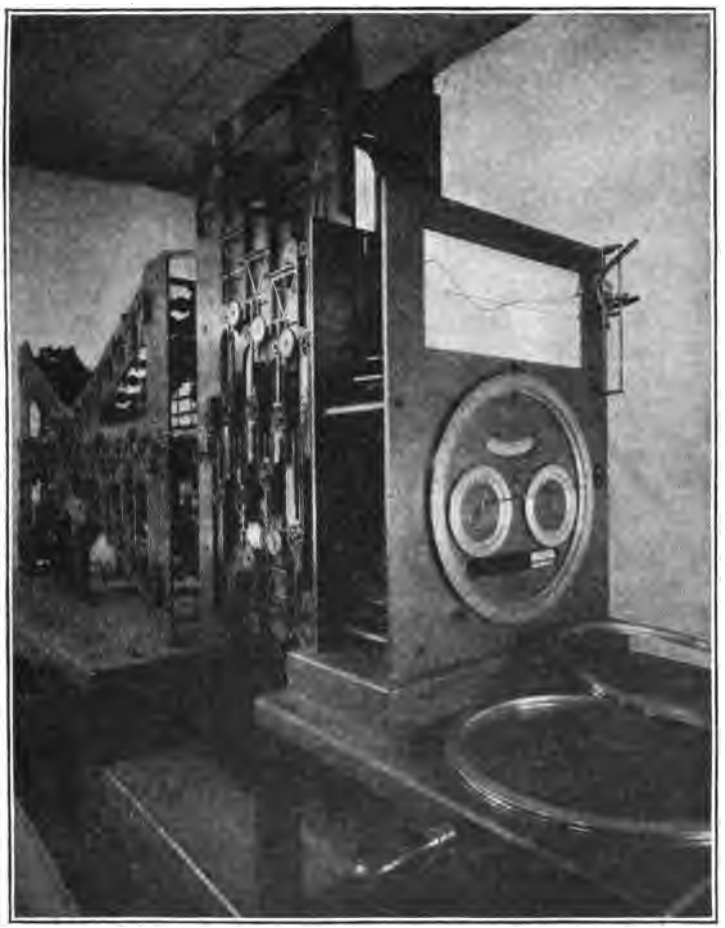


Fig. 27.—TIDE-PREDICTING MACHINE.

In many technical investigations of both theoretic and practical problems, engineers and scientists find themselves confronted by phenomena involving tides and currents. To many of these investigators the Coast and Geodetic Survey has been able to furnish tidal and current information of material help in the solution of their problems.

The study of the tides dates back to ancient times. Several centuries before the beginning of the Christian era the intimate relation between the tides and the moon had been noted. Little progress was made, however, until toward the close of the seventeenth century, when Newton formulated the law of gravitation and proved that the tides were one of its necessary consequences. Since that time the labors of many distinguished mathematicians have contributed to the considerable advance made in the subject. To that advance, the Coast and Geodetic Survey through Ferrel and Harris—the most brilliant of its tidal workers—has made notable contributions.

COAST PILOTS.

Coast Pilots are compiled to assist mariners in the navigation of their vessels, and they serve to supplement the charts issued for that purpose. They contain information which is important to the mariner and much of which is of such a character that it can not be conveniently placed upon a chart. The principal maritime nations of the world publish information and directions of this character for the use of mariners.

As early as 1796 a volume known as The American Coast Pilot (the first Coast Pilot published in America), by Capt. Lawrence Furlong, was published in Newburyport, Mass., by Edmund M. Blunt, and the first edition met with so ready a sale that a second edition of the same work was published in 1798.

The vessels of the Coast and Geodetic Survey while engaged in surveying the coast and harbors of the United States collect much information of importance to mariners which can not be shown on the charts or completely given in Notices to Mariners (a joint publication issued weekly by the Bureau of Lighthouses and Coast and Geodetic Survey), the appropriate agency for its presentation being the comprehensive pages of the Coast Pilots. Similar information can not be collected by private enterprise, except at great cost and with imperfect means, and at the present time all the private publications containing such information relative to the coast of the United States are compilations from Government publications and are generally based on the work of the Coast and Geodetic Survey. Coast Pilots are published and distributed by the Coast and Geodetic Survey at the cost of the printing and binding.

It is manifest that publications of this character must be subject to numerous corrections in the details after the lapse of a few years. To maintain the volume in a useful form, corrections are issued in the weekly Notices to Mariners, insertion sheets, and supplements; and each volume is revised and passed to a new edition when the corrections have assumed proportions that impair its usefulness, or more recent surveys show changes or furnish additions that render the old volume unsatisfactory.

The Coast Pilots published by the Coast and Geodetic Survey contain—

1. A description of the principal lighthouses, light vessels, and fog signals; lists of life-saving stations, storm-warning display stations, and seacoast telegraph stations; and information regarding tides, tidal currents, variations of the compass, etc.

2. Nautical descriptions of the coast and harbors and general information concerning the several bodies of water and harbors, including notes relative to pilots, depth of water, draft of vessels entering the harbors, supplies, facilities for making repairs, usual or best anchorage and other matters of practical value.

3. Sailing directions, with references to prominent objects, dangers, aids to navigation, etc. The arrangement conforms to the order in which these matters would be considered in practice and be available when wanted promptly.

4. Appendices, containing regulations relative to pilotage and harbor control and information regarding meteorologic conditions.

5. Views of important points. These are inserted in volumes which treat of localities which have not yet been surveyed or where they are necessary as an aid to navgiation.

6. An index map showing the limits of the charts covering the localities treated in the volume.

The Coast Pilot publications of the Coast and Geodetic Survey cover the Atlantic and Gulf coasts of the United States, the coast of Porto Rico, the Pacific coast of California, Oregon, and Washington, the coast of Alaska, and the Hawaiian and Philippine Islands.

The compilation of the Coast Pilots necessitates work in the office and in the field. The office work consists of the collection of the latest data from the reports and surveys of hydrographic and topographic parties, from the reports and surveys of the United States engineers engaged in the improvement of harbors and waterways, and from correspondence with local authorities and engineers. This information, in manuscript, is then put in the form which experience has shown to be convenient for the use of the mariner.

For the field work the compilers of the Coast Pilot visit every part of the coast which is treated in the volume; the information collected in the office is verified and, if necessary, corrected on the spot; such additional artificial aids and natural landmarks as are of use to the mariner are noted, and hydrographic examinations of reported dangers and changes are made; pilots, shipmasters, and local authorities are interviewed and the latest information is incorporated, together with such notes as can only be obtained by observation and experience in the locality.

On return to the office from the field the manuscript, corrected to date, is prepared for the printer, and when issued the volumes include, when necessary, a supplement or insertion sheet containing the changes which have occurred since the date of the preparation of the volume and while the matter was going through the press.

A recent publication of the Coast and Geodetic Survey, entitled "Inside Route Pilot New York to Key West," treats of the shallow intracoastal waterways of the Atlantic coast south of Chesapeake Bay and the through passage from New York. It is intended as a guide for those who navigate this coast in very small vessels and are unable to carry complete sets of charts and Coast Pilots. Similar volumes covering the inside waterways from Key West to New Orleans and the inland waterways on the coast of New Jersey have been published. Eventually the entire navigable waters of the coasts will be described as fully as possible.

LEVELING.

Leveling is the operation of determining differences of elevation between any two points on the surface of the earth. There are few surveying or civil-engineering operations in which leveling does not occur in some form. While for many purposes only the relative elevations of points are required, it is desirable for the proper coordination and comparison of leveling results that all elevations be referred to a common datum or surface of reference. In the network of leveling which covers this country the elevations are expressed in meters and feet above the mean level of the sea. The mean level of the sea is assumed to be at the same elevation on the open coasts of the Atlantic and Pacific Oceans and the Gulf of Mexico and it provides a datum easily established and accessible at many widely separated points.

The two principal methods now in use in the Coast and Geodetic Survey for the determination of elevations are by precise spirit leveling and by the measurement of vertical angles. The first is the most accurate method known and differs from ordinary leveling only in the sensitiveness of the instruments used, the care with which the observations are made, and the refinement of the computations; the second is of a lower degree of accuracy, but suffices for many purposes.

The instrument used in precise leveling consists essentially of a telescope carrying a delicate spirit level mounted in such a manner on a portable tripod that it may be quickly and readily placed in a horizontal position. Graduated rods are held at two points, the instrument being placed midway between them. The telescope is sighted first on one rod and then on the other. The difference of the readings of the rods is the difference of height between the two points. The length of sight is usually short and should not exceed 150 meters. By repeating the operation at successive stations the difference of elevation of widely separated points is determined.

Various types of instruments have been used for precise spirit leveling, some of them being nearly like the Y level, used extensively by engineers on construction work, and others differing widely from it. The principal characteristics which distinguish the form of precise level now in use in the Coast and Geodetic Survey are the irreversibility of the telescope and level, the absence of wyes, the rigid fastening of the level vial to the telescope, and its juxtaposition to the latter, in the barrel of which it is countersunk; the use in the construction of the telescope and adjacent parts of a nickel-iron alloy having a very small coefficient of expansion; the protection of the level vial and the middle part of the telescope from sudden and unequal changes of tem-

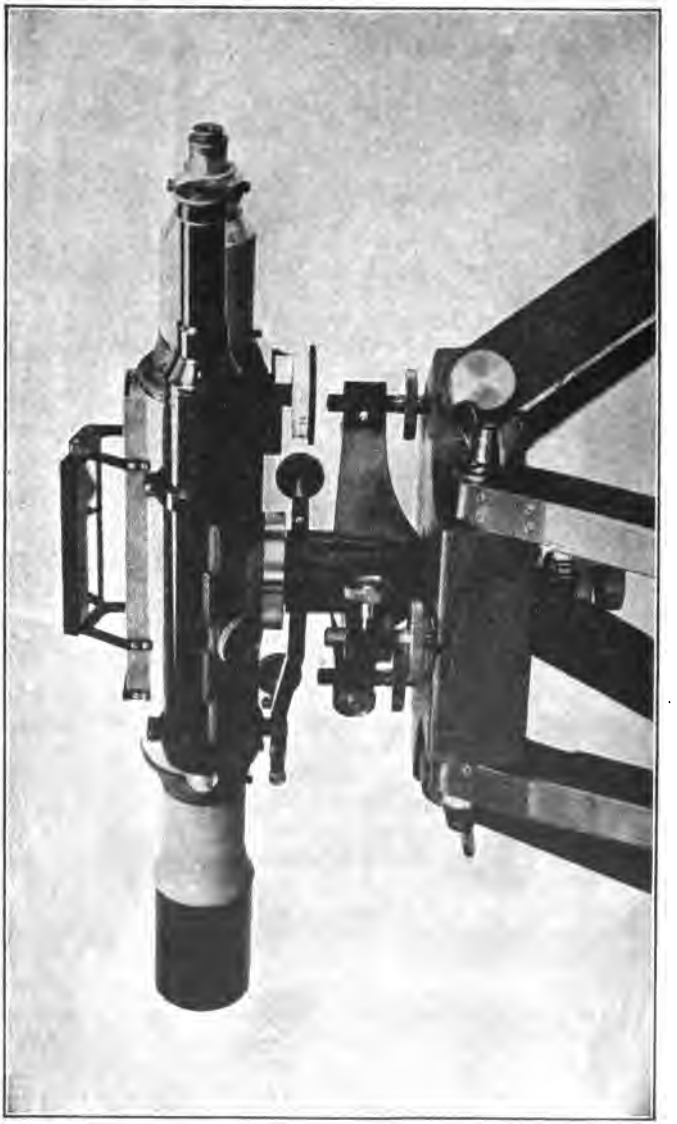


Fig. 28.—LATEST TYPE OF PRECISE LEVEL.

perature by incasing them in an outer tube; and an arrangement by which, without any change of the observer's position, the level bubble can be clearly seen by his left eye at nearly the same instant in which the distant rod is observed through the telescope by his right eye.

Fig. 29.—BENCH MARK.

The readings are made upon a graduated metal strip of an alloy known as gamma steel which has a very small change of length as compared with other metals for any given change in temperature. The strip which is about 1 inch wide fits loosely in a groove of a flat wooden rod about 10 feet long and it is free to move upward for temperature changes, being fastened rigidly only at the bottom of the rod. The bottom of the rod is made of metal and terminates in a flat base of hardened steel about 1 inch square. When leveling along a railroad, the top of a spike, which serves to hold the rail in place, is used as the rod support, while off the railroad the rod is supported on the top of a specially designed pin driven in the ground.

Practically all the precise leveling of the Coast and Geodetic Survey is done along the railroads as it is more economical and the work is more

accessible. Motor-velocipede cars are used for carrying the party to and from work and during the actual leveling. The tripod and level are mounted on one of the cars while the other car carries the rods and an adding machine used to record the results.

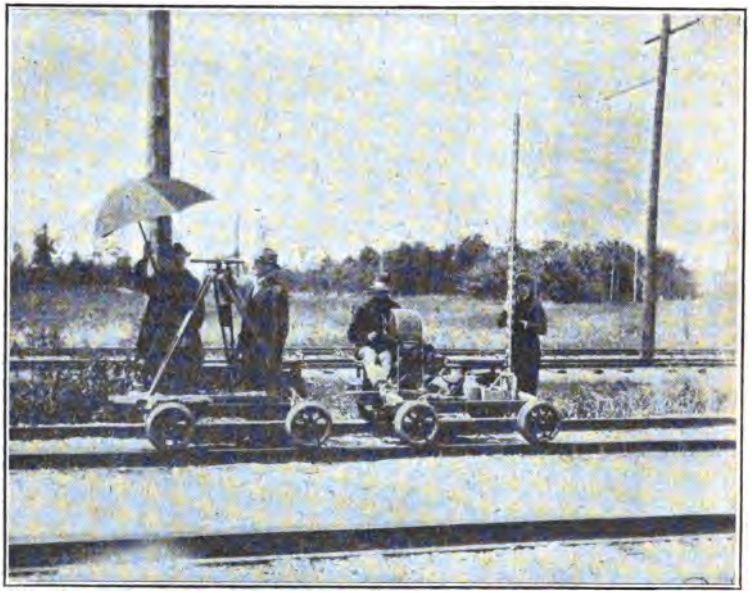


Fig. 30.—MOTOR VELOCIPEDES USED IN PRECISE LEVELING.

A line of precise levels is always run twice, in opposite directions, and in case of disagreement of the results beyond prescribed limits between adjacent bench marks one or more additional runnings are made. Permanent points called "bench marks" are established at short intervals for the use of surveyors and engineers. For the leveling done since 1899 the maximum discrepancy allowed between two measurements on a section 1.6 kilometers (1 mile) long is 5 millimeters, or one-fifth of an inch. For sections of other lengths the discrepancy allowed is made proportional to the square root of the length.

A much more severe test of the accuracy of the leveling is obtained from the closures of large circuits, 50, 100, or 1,000 miles in circumference. Elevations being carried from one point continuously in one direction around the circuit, the computed elevation for the starting point on closing the circuit should agree with that assumed for it at the start if there are no errors in the leveling.

In the network of precise leveling which now covers the United States there are over 100 such circuits, varying in circumference from 100 to 4,700 miles. The lines are so interlaced that each line usually forms a part of two circuits. The greatest error indicated by the circuit

closures in any line of the whole system, involving over 42,000 miles of leveling executed by the Coast and Geodetic Survey, the Corps of

Fig. 31.—ROD USED IN PRECISE LEVELING.

Engineers (U. S. Army), and other organizations, is 2 millimeters per kilometer, or about one-eighth of an inch per mile, while the average error is 0.3 millimeter per kilometer, or about one-fiftieth of an inch

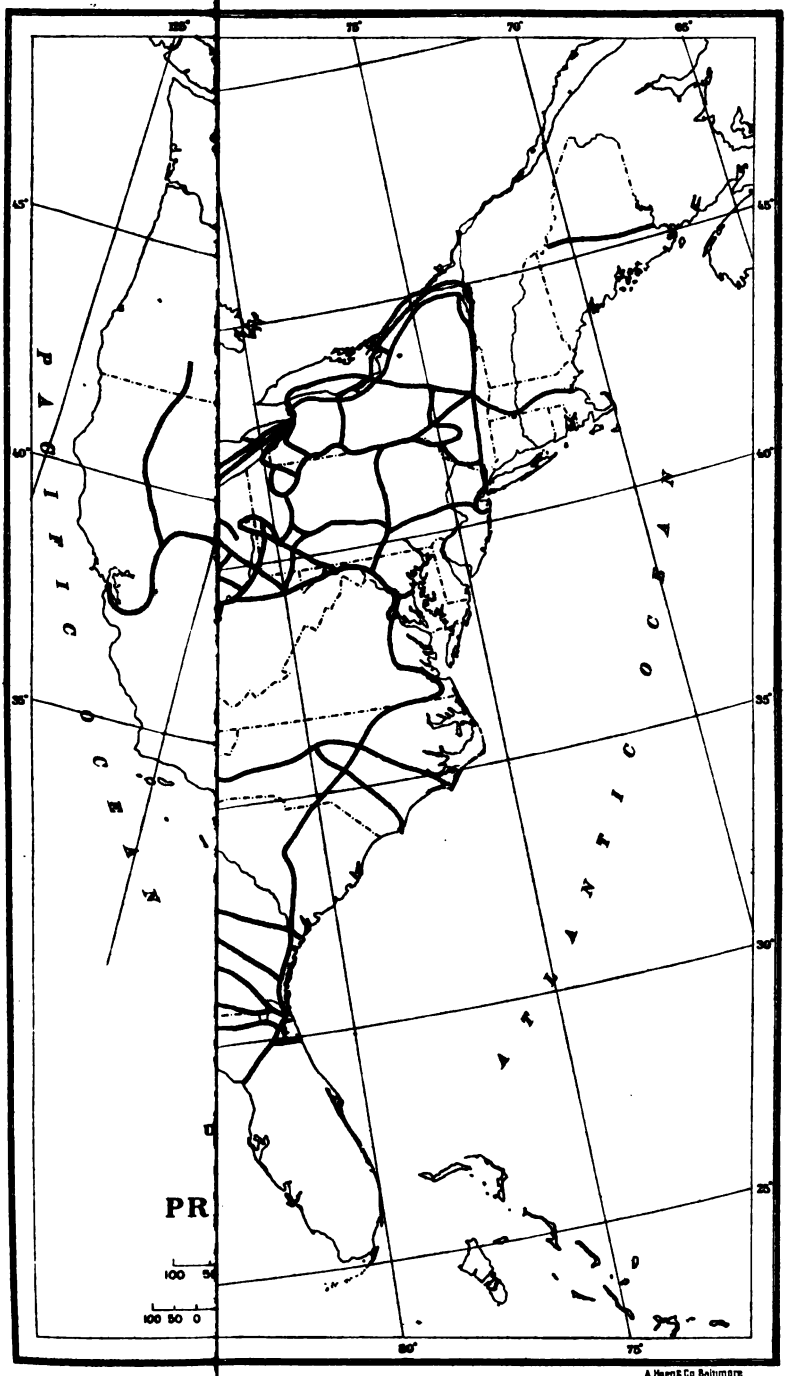
per mile. The leveling done in recent years by the Coast and Geodetic Survey has an average closing error less than 0.2 millimeter per kilometer.

Since the adoption of the present instrument and methods the Coast and Geodetic Survey has completed over 22,000 miles of precise leveling. The average rate of progress of this leveling was about 75 miles per month, each mile being leveled at least twice, once in a forward and once in a backward direction. During the month in which the most rapid leveling was done, 165 miles of the line were completed. The cost of this recent leveling has been from $7 to $16.50 per mile of progress. That is a double-leveled mile.

It is intended to extend the present network of precise leveling over the United States until there will be but a few points in the country which will not be within 50 miles of a precise-leveling bench mark.

Leveling by vertical angles, or, as it is usually called, trigonometric leveling, consists in measuring at any station the angle of elevation or depression of a distant station, and is carried on in connection with triangulation. The sight in this case may be of very great length, and in mountainous regions sometimes exceeds 100 miles. The distance to the station sighted being known, the difference of elevation between the observer's station and the distant point is computed. In making the computations of heights from such observations it is necessary to apply large corrections, on account of the refraction of the ray of light coming from the distant point to the observer. This refraction is very variable, having different values at different hours of the day, on different days, and in different seasons. Because the physical condition of the atmosphere can not be known over long lines of sight, the accuracy of the trigonometric leveling falls considerably below that of precise spirit leveling. The plan followed for preventing the accumulation of errors and improving the elevations determined by trigonometric leveling is to connect these measures at various points with precise-level bench marks and to adjust the trigonometric levels to fit the precise leveling between those points. When this has been done, the resulting heights are of sufficient accuracy for all except very detailed topography. Several thousand points have been so determined in various parts of the United States. The connections with precise-leveling work and other tests of the accuracy of the trigonometric leveling indicate that it is an even chance that the difference of elevation of two points, determined by trigonometric leveling, is correct within 1 or 2 inches to the mile when vertical angles have been observed in both directions over the line.

See also the various leveling publications of the Coast and Geodetic Survey, especially Appendix 8, 1899; Appendix 3, 1903; Precise Leveling in the United States, 1903–1907; and Special Publications Nos. 18, 22, 28, 39, and 41.



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NAUTICAL CHARTS.

Purpose.—Nautical charts are designed primarily for the use of the navigator. They also serve in other ways the interest of commerce, and are valuable for military defense, planning harbor improvements, the study of physical hydrography, and the problems of oceanography.

Chart-making bureaus of the United States Government.—Three bureaus of the Government are authorized to publish nautical charts, but under restrictions which define the duties of each and prevent duplication: The Coast and Geodetic Survey in the Department of Commerce; the Hydrographic Office in the Navy Department; and the Corps of Engineers in the War Department.

The Coast and Geodetic Survey is charged with surveying the coasts of the United States and the coasts under its jurisdiction, with researches to determine the origin and courses of the great ocean currents known as the Gulf Stream and the Japan Stream, and to issue from these surveys charts suitable for the purposes of navigation, commerce, and the public defense. The Hydrographic Office is authorized to duplicate charts issued by other nations, and to publish charts based on surveys by our Navy of coasts not under the jurisdiction of the United States. The Corps of Engineers surveys the Great Lakes and issues the charts necessary for their navigation.

Extent and character of charts.—For purposes of navigation, nautical charts may include large areas like one of the oceans or seas, showing the shores and outlying dangers, and perhaps indicating the principal currents and winds. Charts may also embrace much smaller areas, on larger scales, permitting greater fullness of detail, and thus presenting graphically the channels that can be followed, with the depth of water, the positions of lights, beacons, and buoys, together with sufficient topography to enable the mariner to identify the locality as he arrives in sight of land. The largest-scale charts are generally those of harbors, and exhibiting, as they do, all the important details, including topography, are of great value to the engineer for the study of physical conditions with a view to the improvement and military defense of the harbors.

Series of charts.—To supply the different needs of the navigator the Coast and Geodetic Survey issues various series of charts. On the Atlantic coast, for example, there are four distinct series. In three of these series the charts are located so that each chart overlaps the edges of the adjacent charts in the same series. By this manner the entire coasts are charted on three different scales. In the first series, known as Sailing charts, the scale is small and each chart embraces a

long stretch of coast. They are intended for the use of the navigator in fixing his position as he approaches the coast from the open ocean, or when sailing between distant coast ports. They show the offshore soundings, the principal lights and outer buoys, and such natural landmarks as may be visible from a considerable distance at sea.

The second series is called "General charts of the coast." Their scale is three times as large as that of the sailing charts, and each chart covers a more limited area. They are employed for coastwise navigation when the vessel's course would be mostly within sight of land, with her position fixed by landmarks, lights, outer buoys, and characteristic soundings.

The third series, called "Coast charts," is constructed on a scale five times as large as the general charts of the coast. One inch on these charts represents about 1 nautical or 1¼ statute miles. Such charts are necessarily confined to short stretches of coast and they are made for close coastwise navigation where a vessel's course would carry her inside of outlying reefs and shoals. They are the ones best suited for entering bays and the larger harbors and for navigating the large inland waterways.

The fourth series consists of harbor charts on large scales, intended to meet the needs of local navigation. Harbor charts are not laid out on a uniform scale and according to a rigid system, as is the case in the first three series. Hence they will be found on several scales, and, generally, each chart having no connection with any other one. These charts are much fuller in hydrographic and topographic details than are the charts of the other three series and therefore serve a variety of interests, in addition to navigation, for which the other charts would not suffice on account of lack of information.

Chart-making material.—Elsewhere in this publication have been described the several lines of work of the Coast and Geodetic Survey. Its various field activities are carried on to supply the information needed to prepare the charts, and to supplement their use with the aid of Coast Pilots, tide tables, etc. All the field data are sent to the Washington office (or, in the case of the Philippine Islands, to the Manila office), where the triangulation and other geodetic and magnetic work and the tidal data are examined by expert computers who make the necessary adjustments to connect them with work already done. Hydrographic and wire-drag surveys are always unfinished when received from the field, owing to the necessity of supplying certain information and checks which can be done only in the office. Expert hydrographic draftsmen there complete the plotting, inking, and verification of these sheets.

To one not acquainted with the subject it will be a surprise to learn how much original survey material and published data enter into the preparation of a chart. The following statement shows the material used in preparing one of the Alaska charts, and is well below the average in the quantity of material required:

Material used in constructing a typical Coast and Geodetic Survey chart.

Chart No.	Approximate area (square miles).	Original material.				Compiled material.		
		Volumes of field records.	Topographic sheets.	Hydrographic sheets.	Surveys by other organizations.	Larger-scale C. & G. S. charts.	Foreign charts.	Volumes of Coast Pilots, Light Lists, etc.
8,102	1,600	1,000	102	124	17	10	5	8

Construction of the chart.—The surveys and other field data having been examined and adjusted, the preparation of the chart may be started, the first step being the construction of a projection. This is the term applied to the framework of lines found on nearly all nautical charts, and which represent the parallels of latitude and meridians of longitude. Sometimes, for the sake of simplicity, only the intersections of these lines are shown on the body of the chart.

Owing to the curvature of the earth's surface, it is not possible to represent it upon a plane surface, such as a sheet of paper, without introducing some distortion and the sacrifice of some desirable quality. Many different types of projection have been devised, but, with the exception of a few special charts, the Coast and Goedetic Survey employs only two kinds, the Mercator and polyconic, of which brief descriptions will be given.

Mercator projection.—The Mercator projection is used for the principal charts of the coast and for all oceanic areas. The meridians of longitude are represented by parallel straight lines, and the parallels of latitude by straight lines separated by spaces that increase between successive parallels when proceeding from the equator toward the poles. A glance at a globe will show that the actual distances between the meridians on the earth's surface diminish as one goes toward the poles, while there is practically no difference on the earth between the parallels. It is evident, therefore, that the scale of a Mercator chart becomes larger and larger toward either pole. This variable scale, which increasingly exaggerates all details as one gets farther from the equator, constitutes the principal drawback to this projection. It has, however, certain advantages for the navigator that are not found on other projections.

Polyconic projection.—The use of this projection is confined mostly to harbor charts and to surveying purposes. It possesses the advantage over the Mercator, and most other projections, of showing the directions and distances of all points in their correct relation to each other, provided the projection is not extended over too large an area.

Details of chart construction.—With the projection as a framework and guide for their proper location, the details of the land area are copied from the topographic field sheets. If the chart is on a large scale, such as a harbor chart, where it is desired to show every detail, the copy may be an exact one of the field sheet. If, however, the chart is on a small scale, minor details are omitted and others are generalized.

To show the depths on the water areas of the chart, the soundings are copied from the hydrographic field sheets and correctly located, as in the case of the topography, with reference to the meridians and parallels. For the sake of clearness, a selection is made from the closely spaced soundings on the field sheet, only those soundings being copied which are necessary to plainly show the configuration of the sea bottom. On large-scale charts the outline of the bottom is shown in minute detail, as was done in copying the topography, and likewise the smaller the scale the greater the generalization and the larger the number of details omitted.

In addition to the representation of hydrographic and topographic features the charts contain much information in condensed form relative to the variation of the magnetic compass, tides, currents, meteorology, and descriptive notes concerning channels, dangers to navigation, and other related subjects.

The names are now placed on the drawing, which is then turned over to another cartographer, who verifies every detail, paying especial attention to those features whose omission or misplacement might result in disaster to the navigator.

At this stage the chart is known technically as a rough drawing or compilation; rough, however, only in the sense that pains were not taken to make the lines smooth or the figures and letters well-shaped, as they will finally appear on the printed chart. The work is the product of the engineer rather than of the artist.

From this point the work may progress along any one of a number of lines. Various methods of printing charts are in use and the method determined for each particular chart determines the proceedings from this point. It is, therefore, necessary here to state briefly the methods of printing in order that the reader may understand the reason for this divergence.

The following methods of printing are used in the Coast and Geodetic Survey:

1. Plate printing.
2. Lithographic printing.

(*a*) By transfer from engraved copper plate.

(*b*) Photographic process printing with the aid of photography.

Formerly it was the custom of all nautical chart producing organizations to print the charts directly from engraved copper plates. Engraving has been a familiar art for many years, whereas lithographic printing is of comparatively recent development. Even to-day there is no other method available which produces such sharp, clear outlines, and

such legibility of minute detail, as that obtained in an impression from a good copper plate. The method, however, is a slow and laborious one. Most of the work must be done by hand, with the result that two men operating one press can print only from 80 to 100 charts a day. Obviously, therefore, the method is not suited to quantity production. The method used also casuses considerable distortion of the resulting print which, in a product of this character, it is very desirable to avoid. For these reasons the method of printing direct from copper plates is being discarded by the Coast and Geodetic Survey as rapidly as the transition to lithographic printing can be effected. A few charts are still printed direct from the copper plates, but these are confined to charts of remote or unimportant localities for which the demand is so limited that only a few need be printed at any one time.

Printing by transfer.—Even if the chart is not to be printed from the copper plate there are cases where it is desirable to have the chart engraved on copper. The compilation of the chart is a tedious and expensive undertaking, requiring months to complete. Once completed, however, the compilation of a chart of a well-surveyed region is suitable for use for many years, it being only necessary to correct it for natural or artificial changes which occur with the lapse of time. It is, therefore, desirable that the original compilation be preserved on a medium which is permanent, not subject to change in varying atmospheric conditions, not easily damaged, and on which old work can be erased and changes made, even a number of times in the same locality.

Copper plates possess these qualities to a much greater extent than any other material upon which the drawing can be made. On the other hand, the very qualities inherent in the copper which give it these attributes result in certain drawbacks. Because copper is permanent and durable it is hard to work on. In many cases it takes longer to engrave a chart on copper than it does to draw the same chart on vellum, but as drawings deteriorate or are worn out by frequent corrections, and have to be entirely redrawn, engraving, in addition to its clearness, may be more economical even where the first cost is greater, except in very changeable areas, where resurveys are frequent and cover the major portion of the chart.

As so many charts consist of one important harbor frequently resurveyed, with extensive surrounding areas where resurveys are practically unnecessary, the advantage of having charts of this character on permanent material is apparent. Corrections can be made in one section for all time without an entire redrawing of the whole chart whenever such corrections are needed. Corrections are more difficult to make on copper and, if extensive, involve the use of time-consuming electrotyping processes. This fact constitutes the most serious objection to the use of copper, as it is important that the navigator should be furnished the results of new surveys with as little delay as possible.

A careful weighing of these advantages and disadvantages has led to the conclusion that certain charts should be preserved on copper whereas others should be on a less permanent material, the character of the region charted being the detemining factor. Thus, a small-scale chart of the inside waters of southeastern Alaska should be on copper, for no extensive changes, either natural or artificial, involving large corrections to the chart need be anticipated. On the other hand, such a chart as the large scale one of New York Harbor is not suited to engraving on copper because of the changes which must constantly be made over all parts of it, in order that it may be kept up with the developments of the port.

In order then that advantage may be taken of the desirable qualities of the copper plate without being compelled to suffer the disadvantages of printing directly from it, a method has been developed by which the work engraved on the copper plate can be transferred to an aluminum printing plate and printed on the lithographic presses. An impression from the copper plate is pulled on a specially prepared transfer paper. This impression is then laid down on the aluminum printing plate and run through a press by which means the work is transferred to the printing plate, which is then further treated to fix the work and render the plate suitable for printing from it.

Photographic process printing.—In this method, after the compilation of the chart is completed, the rough drawing is covered with tracing cloth or vellum through which the details are visible and these are traced with pen and india ink, converting rough lines into smooth and ill-shaped letters and figures into well-shaped ones. Corresponding care is taken in the reproduction of the various conventional symbols used to delineate the topographic and hydrographic features, so that the completed tracing is not only accurate as to location of these features but is also of the highest artistic quality.

This drawing is then photographed in sections, from four to six negatives being made, depending upon the size of the chart, which reproduce every detail and are exactly of the scale of the tracing. In this work the skill of the photographer is taxed to obtain the greatest possible sharpness and definition and to secure negatives which fit each other exactly, so that when laid down side by side each line exactly joins its continuation on the adjacent negative.

These negatives are then exposed on a sensitized aluminum plate with the result that when developed and properly treated the drawing is reproduced as a positive on the printing plate and is ready for use in printing.

Prior to the completion of the compilation the method by which the chart is to be printed has been determined. If it is to be reproduced on copper the compilation is sent to the engraving section.

Engraving of charts.—The first step in this process is to construct the projection on the copper plate. The compilation is then photographed in sections on a transparent medium, producing what are called ma-

trices. These matrices are then laid down on the copper plate, a small area at a time, each area being fitted into place by fitting the projections seen on the matrix to the projection on the plate and the work is transferred from the matrix to the copper, affording the engravers an exact copy of the chart from which to work.

The work is then engraved upon the plate, each detail being reproduced exactly in the position which it occupied in the compilation. In this engraving the artistic quality, which, as we have already seen, was lacking in the compilation, is added. When the old method of printing direct from plates was in use the plate was engraved negatively, so that the print from it would be positive. With the adoption of the newer method of printing on an offset press from a transfer made from an engraved plate, the method of engraving was changed to positive. This results in a negative on the transfer paper which again becomes a positive on the printing plate.

Most of the work of the engraver is done by hand, and this part is necessarily slow and laborious. Some parts, however, such as the soundings and certain conventional symbols, are cut by mechanical appliances. Thus, a chart upon which hydrography predominates can be engraved in about the time required to make the tracing on vellum.

In engraving the chart the same care that was used in making the compilation is exercised by the engraver to insure absolute accuracy. When the engraving is finished an impression is pulled from the plate, verified by the engraver, and any necessary corrections made. Another impression is then pulled, which receives a final verification by the draftsman.

When the plate is finished and found to be correct in every detail, it is turned over to the electrotyper who produces an "alto," which is stored for future use. This is necessary because, durable as the copper is, it eventually becomes so worn that good impressions can no longer be obtained. When the plate approaches that condition a new "basso" is made by electrotyping, thus producing in a few days' time a new plate the equal of the former at its best.

Final details.—The final step in preparing the chart, irrespective of the method by which it is to be printed, is the drawing of the symbols of the lighthouses and buoys where they belong, and also the compasses where they will be most convenient for the use of the navigator. The application of this information is delayed until the chart is ready to go to press for the reason that changes in these aids to the navigator necessarily are made with considerable frequency, and it is essential that all these details be correct on the date when the chart is issued.

Printing.—Over 94 per cent of Coast and Geodetic Survey charts are now printed by lithography, and of these over 93 per cent are printed offset; that is, the paper does not come in contact with the aluminum printing plate, but instead the impression is made on a rubber blanket from which it is offset to the chart paper. This process gives sharp and unbroken lines. The offset process is used for the black only, which

is, in fact, the chart. Colors are used to accentuate certain features such as the red buoys and on small charts, the lights. The land is covered by a tint, and on some charts shoal waters are tinted blue. The object is, of course, to improve legibility. Both rotary and flat-bed presses are used.

New editions of charts.—In most cases but a short time elapses after a new chart has been printed before it needs revision to keep it up to date. This will be understood when it is stated that there are over 16,000 lighthouses, beacons, and buoys maintained along our coasts, and among these there were over 1,300 changes within a year. Then the river and harbor improvements, under the Corps of Engineers, result in deeper and wider channels, or new breakwaters, which must be noted on the charts. The chart must also keep pace with the changes in the water fronts of harbors and the growth of cities and towns along the coast, so that the navigator will be able to identify his position on the chart by reference to these objects.

Besides these changes due to the works of man, the great natural agencies are also constantly at work altering the features shown on the charts. The action of currents and waves is continually cutting away or building up the shore, particularly on sandy coasts exposed to storms, and while these visible effects on land are being produced, others even more important are going on beneath the surface of the water; channels and shoals shifting, new ones coming into existence or old ones disappearing. All these changes from the various sources indicated give an idea of the problem of keeping a chart up to date and why it is necessary to print small editions and revise the charts frequently.

The publications of the Coast and Geodetic Survey are sold to the public at a price which is estimated to cover only the cost of paper and printing. The main purpose in selling the charts at this low rate is to encourage the use of the latest editions as the employment by mariners of an old chart, instead of the latest edition, is highly hazardous. A number of vessels have been lost due solely to the use of old charts. At present 658 different charts of the waters under the jurisdiction of the United States are being published, and the number of copies issued during the fiscal year ended June 30, 1919, was 290,537.

Reading charts.—A nautical chart is essentially a diagram for practical use by navigators. All ornamentation and unnecessary details are studiously avoided. The symbols employed to represent the various features are the result of many years of experience. To aid in interpreting the hydrography and to make plain the shoals and passages, depth curves are given on the charts. The shoaler areas are made conspicuous by the use of fine dots (sanding) and frequently a blue tint is used for the same purpose.

OCEANOGRAPHY.

The primary interest of the Coast and Geodetic Survey in oceanography is well defined as being solely connected with the physical characteristics of the ocean as distinguished from the life of the ocean.

These physical characteristics have been divided by some oceanographers under two general headings: First, static oceanography, including the temperature, density, and chemical properties of water, depth and character of bottom, etc.; second, dynamic oceanography, including such phenomena as tides, currents, land formations, waves, etc.

The first oceanographer in the United States was Benjamin Franklin. This is evidenced by an excellent map of the Gulf Stream published in 1770 from information received from American whalers and merchant ship captains.

The first oceanographer of the Coast and Geodetic Survey was Lieut. George M. Bache, who was a direct descendant of Franklin. Lieut. Bache, while engaged on deep-sea exploration in the Gulf Stream off the coast of Virginia, was washed overboard from the United States Coast Survey brig *Washington* and lost with 10 members of his crew on September 8, 1846.

Our present knowledge of oceanic depths adjacent to and along the steamer tracks between our Atlantic and Pacific coast ports, including the approaches to the Panama Canal, has, since the termination of the World War, been amplified to a large extent by the Coast and Geodetic Survey's vessels returning to their stations on the Pacific coast.

Depths of the ocean.—It so happens that the greatest known depths of both the Atlantic Ocean and the Pacific Ocean are located in waters adjacent to islands belonging to the United States. In the Atlantic, north of Porto Rico, a sounding of 4,662 fathoms (27,972 feet) has been obtained, and in the Pacific, off the east coast of the Philippines, the greatest known depth of all the oceans was measured by the German ship *Planet*. Here the bottom is below the level of the sea a distance of 5,348 fathoms, or 32,089 feet, which is the equivalent of more than 6 land miles, a depth greater by 3,087 feet than the greatest known height of the Himalayas.

To obtain measures of the great oceanic depths several successful sounding machines have been perfected, notably the one designed by Sigsbee, with which the United States Coast and Geodetic Survey ships are equipped.

All deep-sea sounding machines are dependent on the use of a very fine steel measuring wire with a heavy detachable shot as a sinker. The amount of wire passing over a recording measuring wheel gives the depth in fathoms or meters as may be desired. This sinker and wire are allowed to run out from a revolving drum with all freedom possible, but even under the best conditions it takes, for example, a full half hour for the shot to reach bottom at 3,000 fathoms; and in greater depths the time of falling of the shot and wire is rapidly increased by the friction of the longer wire.

Nothing is so impressive of the magnitude of the depths of the ocean as the watching, second after second, minute arter minute, for a half hour or more, the rapidly revolving drum from which the sounding wire is unfolded in its downward fall. And when the bottom is struck and the shot is automatically detached, as indicated by the slight slackening and tremor of the wire conveyed to the surface, there comes a sudden realization of the 3 or 4 miles of elevation of the observer above the bottom of the ocean.

Temperatures.—Oceanographic temperature observations are made on a larger and stronger wire than that used for soundings, a series of specially devised self-registering capsizing thermometers being secured to the wire at different points as it is lowered. When the lower end of the wire is at the desired depth, a weight, called a messenger, is started down which not only capsizes the first thermometer, but also releases a second messenger which is attached to it. The second messenger then continues its journey to the second thermometer which it both capsizes and causes to release a third messenger, and so on for a period of a half hour or more until the last thermometer of the series has registered its temperature by capsizing.

Currents.—A statement of oceanography as connected with the work of United States Coast and Geodetic Survey would be incomplete without some mention of the work of that Service in the study and investigation of the great ocean river known as the Gulf Stream. To this problem, under special authorization by Congress, much time and energy has been devoted, as is shown by the many publications giving the results and discussion of the work of such oceanographers as Bache, Pourtales, Mitchell, Sigsbee, Pillsbury, and others. The work of the United States Coast and Geodetic Survey ship *Blake* under the command of Sigsbee and Bartlett, is particularly well known through the two volumes of Agassiz issued under the title "Three Cruises of the *Blake*."

To measure ocean currents at the surface where the depths are not too great to anchor a ship by ordinary means is a comparatively simple undertaking. At greater depths it is a problem that has not been satisfactorily solved, although Pillsbury, in his famous investigations of the Gulf Stream, while in command of the United States Coast and Geodetic Survey ship *Blake*, succeeded by the use of specially designed machinery in anchoring the *Blake* at the very wonderful depth of 2,100 fathoms (12,600 feet).

The measure of the motion of a suitable floating object in direction and velocity in reference to a fixed point sufficiently indicates the work that is necessary in the measurement of surface currents. But underwater measurements involve not only the register of a revolving wheel representing the velocity of the movement of the water, but also the register of the direction of the movement as measured by some form of a compass. Several very ingenious current meters have been devised that will accomplish this purpose, but are too complicated for an adequate description in this pamphlet.

Ocean tides.—The subject of tides, as connected with the work of the United States Coast and Geodetic Survey, has been described in a separate chapter under that heading, but it has one phase which is so clearly one of oceanography that it will be briefly mentioned. It relates to the question of the origin or cause of the dominant tides as developed in the Stationary Wave Theory of Tides, by Dr. Rollin A. Harris, of the Survey.

From the viewpoint of the ordinary student, the problem of the tides is one that was settled in its main features as long ago as the discovery of the laws of gravitation by Newton. As a matter of fact, it is only in recent times that anything like a satisfactory explanation of the dominant ocean tides has been developed in a practical form. The reason assigned for this is that "definite or applicable theories concerning the causes of existing tides were impossible before the depths of the oceans had become generally known."

Knowing the depths and the shape of the ocean basins, knowing the laws of the oscillating movements of water in such basins, and knowing the laws of the action of the oceans of the tide-producing forces of the moon and sun, it is theoretically possible to calculate the character and extent of certain great stationary waves, extending from continent to continent, or otherwise as the shape of the ocean basins may demand, whose period of oscillation shall correspond to and be maintained by the periodic action of the tide-producing forces.

That such oscillating oceanic waves do exist had been surmised for some time, but it was left to Harris by his development of the cotidal lines of the oceans and the dynamic laws of the fundamental movements of ocean waters to demonstrate that the Stationary Wave Theory of Tides is in accordance with the actual observations of the phenomena of the rise and fall of the tides.

Other physical phenomena.—Other physical phenomena of oceanography within the province of the Coast and Geodetic Survey, such as the salinity, density, and composition of sea water, etc., are many and constantly increasing as the subject of oceanography is enlarged on its many sides.

Apparently there is no sphere of both scientific and practical endeavor which is at the same time so vast and so little exploited as that of oceanography. In fact, the great depths of the oceans with their unknown physical and biological features are perhaps the only remaining portions of the world that can be justly said to be still unexplored.

GRAVITY.

Gravity observations are an important and essential part of a geodetic survey.

While operations for the measurement of the size of the earth by extended and connected systems of triangulation are of necessity confined to the land—that is, to one-third of the earth's surface—gravity observations can be made at disconnected points anywhere on the earth's surface, on islands, in the ocean, and, with less accuracy, even on ships. From such observations the earth's compression—that is, its shape, can be deduced by mathematical processes with a high degree of accuracy.

A knowledge of the intensity of gravity is also essential in meteorology and for the determination of many physical constants, such as, for instance, the mechanical equivalent of heat. By means of gravity determinations an extensive research has been made by the Coast and Geodetic Survey to determine variations from the normal densities of the materials in the outer portion of the earth. (See article on Geodesy on p. 97.)

Gravity is the term used for the tendency of bodies to fall toward the earth. It is the resultant of two opposing forces—gravitation or the attractive force of the earth and the centrifugal or repelling force due to the earth's rotation.

The variation of the force of gravity at different places on the earth's surface was first discovered by Richer in 1672. He found that a clock which kept accurate time at Paris, France, lost two minutes daily when transported to the island of Cayenne, South America, though there had been no change in the length of the pendulum. Later it was found that gravity varies with the latitude, with the elevation, and with the character of the topography of the surrounding country. Thus, a mass weighing 200 pounds at sea level at the Equator will weigh approximately 201 pounds at sea level at either pole; a mass weighing 400 pounds at sea level will weigh approximately 399 pounds at an elevation of 5 miles in the same latitude; and a given mass will weigh more at the top of a sharp mountain peak than if it were at the center of an extensive plateau of the same elevation as the peak, providing the latitude is the same in both cases. It is understood that these weights are recorded on a spring balance and not on beam scales.

The pendulum forms the most precise as well as the most convenient way for measuring gravity. The early forms of gravity pendulums were made about 1 meter in length and had a period close to one

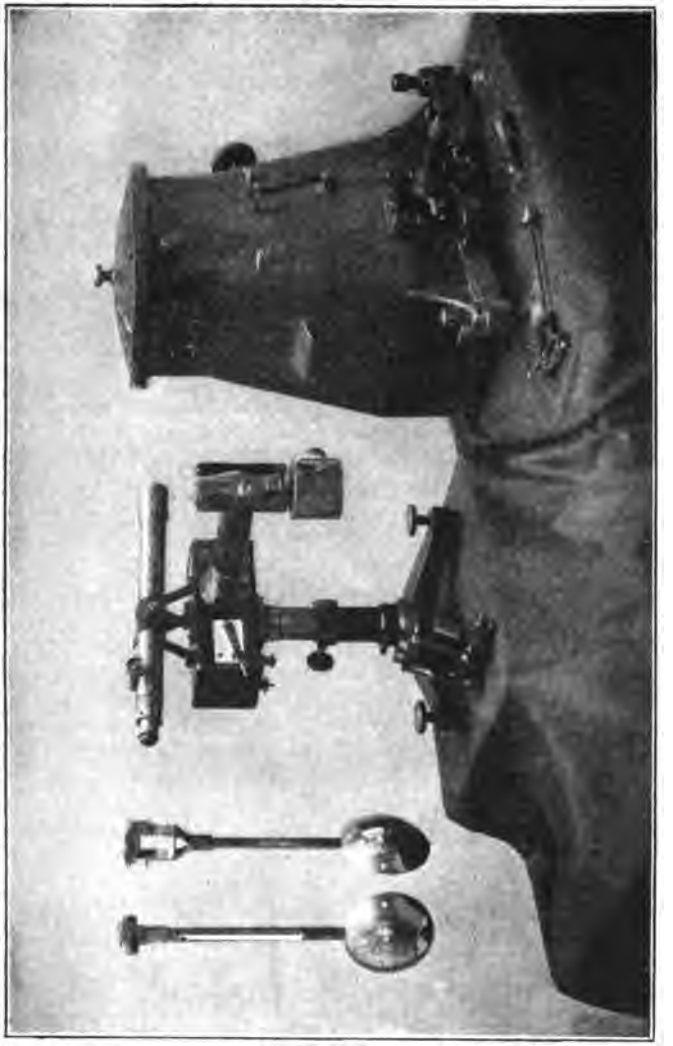

Fig. 33.—HALF-SECOND PENDULUM AND APPARATUS.

second. These pendulums were difficult to handle and transport on account of their large size, and as they were swung in the open air they did not give very accurate results. Some forms were reversible for measuring the absolute value of gravity while others were swung in only one position and could be used only for measuring differences of gravity.

It is a difficult matter to determine accurately the absolute force of gravity for a station, even with the greatest care and a large number of observations. On the other hand, it is comparatively easy to determine with great accuracy the difference of gravity between two places with the invariable pendulum. All observations for obtaining the values of gravity in the United States are made by the relative method. The base station for the United States is a brick pier in the basement of the Coast and Geodetic Survey office in Washington. The value of gravity at that pier was obtained by the relative method from Potsdam, Germany, where the absolute value of gravity was obtained from many observations throughout a long period of years. All values of gravity in the United States, therefore, are referred to the absolute measurements at Potsdam.

The form of pendulum now used by the Coast and Geodetic Survey differs very materially from the early forms and was designed and constructed by members of the Survey in 1890. Like the pendulum designed by Dr. R. von Sterneck in Austria several years previous to this time, it is only one-quarter of a meter long and has a period of oscillation of about one-half second.

The gravity apparatus in present use in the Survey consists of the following essential parts: Three pendulums, an air-tight brass case in which the pendulums are swung, a telescope for observing the oscillation of the pendulums, two chronometers, several thermometers, a manometer for measuring the air pressure within the case, and an interferometer for measuring the movement of the case caused by the swinging of the pendulum. The pendulum is a simple stem and bob of solid bronze and differs from an ordinary clock pendulum in having a small agate plane attached to its head which rests on an agate knife-edge in the case and in having no machinery to drive it or count its oscillations. During the experiment the pressure of the air within the pendulum case is reduced to less than one-tenth of one atmosphere. The resistance of the rarefied air and the friction between the agate knife-edge and the plane are so small that a pendulum will swing continuously for more than 12 hours, even though its initial arc is only about one-fifth of an inch.

The period of oscillation of the pendulum is observed and compared with the beat of the chronometers at the beginning and end of each 12-hour swing, and from these comparisons the average period of oscillation is computed. The pendulum is made of such a length that its period is nearly, but not quite, equal to a half second, and during a period of from three to six minutes it makes one less oscilla-

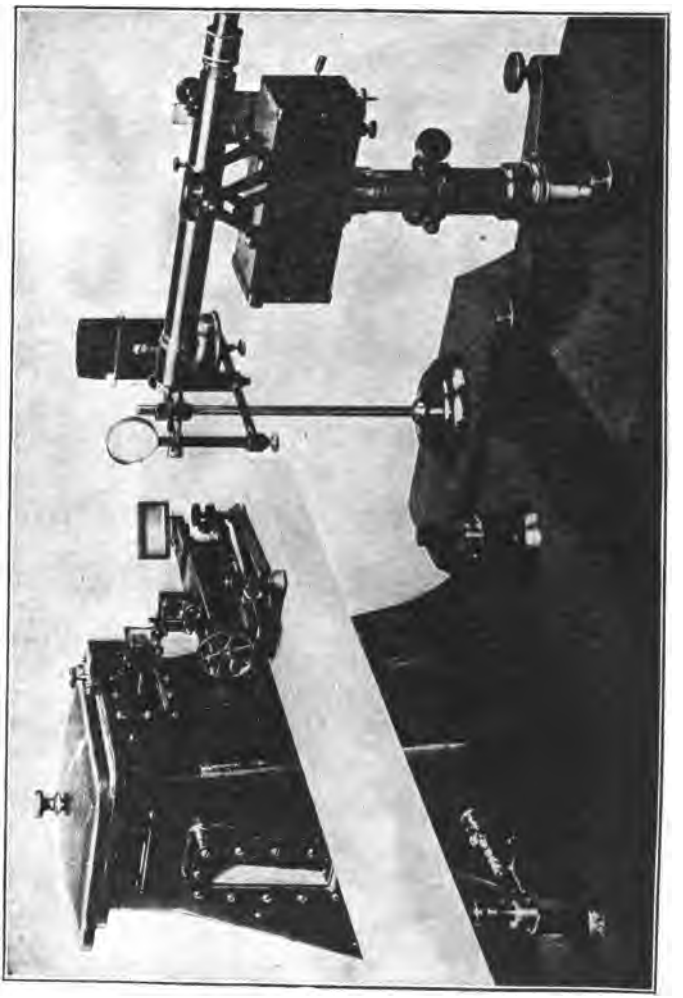

Fig. 34.—INTERFEROMETER FOR MEASURING FLEXURE OF PENDULUM SUPPORTS.

tion than the number of half seconds registered by the chronometer. By an ingenious mechanical device a beam of light is thrown into the pendulum case at each beat of the chronometer and it there falls upon two small mirrors. One of the mirrors is attached to the head of the pendulum and swings with it, while the other is permanently fixed to the support and just to the side of the pendulum. When the pendulum is at rest, the two slits of light as reflected from these two mirrors appear as a single horizontal line, but in any other position of the pendulum the line of light as reflected from its mirror will appear above or below the line from the other mirror. Observing a coincidence consists in noting the time when the two slits of light appear in the same horizontal line and the observing of two or more consecutive coincidences enables one to deduce the period of oscillation of the pendulum in terms of the chronometer time.

The measurement of the force of gravity at a station, to be acceptable, must not have a probable error greater than 1 part in 200,000. An actual error of 1 part in 200,000 corresponds to an error of only one one-millionth of a second in the period of oscillation of the pendulum. Such accuracy is not easily conceivable, but it is attained with no great difficulty by an experienced observer. Care is taken to keep the pendulum apparatus at as nearly a constant temperature as possible and all variations are carefully observed.

One of the corrections which must be applied to the observed time of oscillation of the pendulum is due to the movement of the case resulting from the swinging of the pendulum. The case is a rectangular brass box about 10 inches square at the base and 11 inches high (inside dimensions), weighing 100 pounds. It is either placed on a solid concrete floor or an especially prepared brick or concrete pier. In spite of these precautions, the swinging of the pendulum through its very small arc causes a rocking of the case, and this in turn affects the period of the pendulum. This small movement of the case is measured by the interferometer, a very delicate instrument which depends in principle upon the interference of light waves. Distances as small as one ten-millionth of an inch, one-twentieth of a wave length of sodium light, can be measured with it. Vibrations of the ground due to the passing of a team a city block away or a train a mile away are easily detected. During such disturbances observations with the interferometer to determine the flexure of the pier and pendulum case can not be made. Some idea of the delicacy of this measurement may be obtained if it is noted that the correction to the period of the pendulum for flexure usually amounts to about one one-millionth of a second.

In order to eliminate from the gravity observations errors due to the rate of the chronometer it is necessary to determine its error within a few hundredths of a second of time both at the beginning and end of a series of observations with the pendulum. This was formerly done by making time observations on the stars with an astronomic

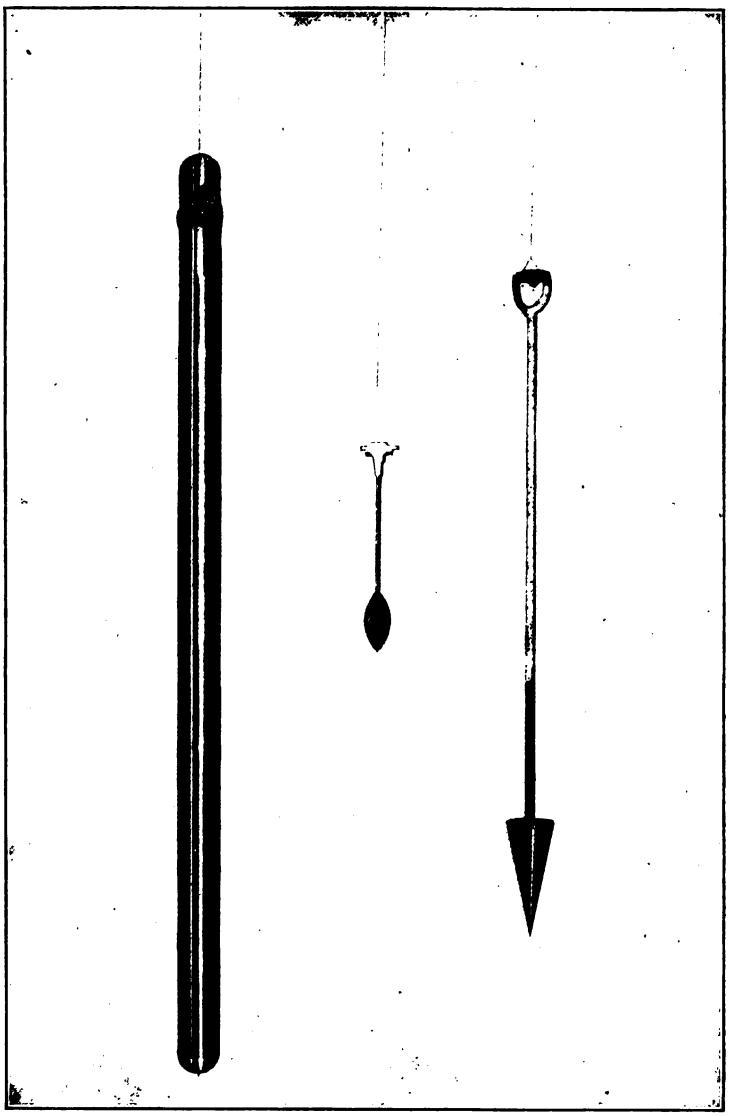

Fig. 35.—VARIOUS TYPES OF PENDULUM.

At the left the Peirce invariable seconds pendulum, at the right the Kater invariable seconds pendulum, and at the center the original half-second pendulum of the Coast and Geodetic Survey.

transit. During the last few years satisfactory results have been obtained by the use of the noon signal sent out from the Naval Observatory over the commercial telegraph lines. This method has decreased the time and cost of occupying a station very considerably without lowering the accuracy of the work. The gravity determinations can now be made at any time without regard to the weather and one observer can do the work alone. A second observer was necessary when time observations were made at each station.

Apparatus is now being assembled and tested for receiving in the field wireless time signals sent out by the Naval Observatory from the Annapolis wireless station. This apparatus will make it possible to locate gravity stations in out-of-the-way places not reached by telegraph lines without the necessity of making time observations with the astronomic transit.

Two new sets of pendulums have recently been constructed in the instrument division of this Bureau. The only difference between these new pendulums and the old ones is the material of which they are made. The new pendulums are made of nickel steel or invar and have a temperature coefficient which is only about one-fifteenth that of bronze, the material used for the old pendulums.

Temperature control has been a very serious problem with the bronze pendulums, an error of temperature of 1° causing an error in the result four times the maximum allowable error. A constant-temperature room at each station has been a necessity. With the invar pendulums it will be possible to have stations out in the open country or on mountain peaks using only a tent for protection.

There are now 275 gravity stations in the United States. They are distributed quite uniformly over the whole country except in a few critical areas where they have been placed close together to make possible some special scientific investigations in connection with geology or isostasy.

See also Special Publication No. 40 of the United States Coast and Geodetic Survey, which contains the results of 217 gravity stations in the United States.

GEODESY OR MEASUREMENT OF THE EARTH.

It is natural that from the earliest times man should have inquired and speculated about matters concerning the earth upon which he walks and on which he spends his life, but his first crude ideas about its shape and magnitude were not developed up to the point of a fair resemblance to the facts until the civilization of the race had already grown old.

Geodesy is a natural development of the simpler operations of land surveying, but, unlike the latter, takes into account the sphericity of the earth. Land surveying was practiced from a very ancient date. Thus, in a papyrus of a date earlier than 1700 B. C. the author stated that his work was a compilation from older manuscripts. The notion that the earth's surface could not be a plane, but must be curved like the surface of an immense ball, should have been apparent to dwellers upon the seashore; yet the fact that the earth is, roughly speaking, spherical was not appreciated for many centuries after civilization had developed to such an extent that land surveying was practiced. The step from plane to spherical surveying was an important one, and when it was made geodesy, allied to practical astronomy, became an independent branch of science.

It is the glory of the famous School of Alexandria to have produced, shortly before the beginning of the second century before Christ, the first measure, and a little later a second measure, of the earth's curvature—that is, of the radius of the sphere. It is also remarkable that the principle then employed has been used ever since. Essentially, it involves the determination of the distance between two remote points north and south of each other and of the meridian altitudes of the sun or of some star as seen from the two ends of the measured line. The difference of the measured altitudes gives the curvature of this arc of the great earth-sphere expressed, say, in degrees. This being known, as well as the length of the arc, the circumference or the radius of the sphere can be computed. After these first measures by the School of Alexandria a thousand years passed before a similar attempt was made—this time by the Arabs in Mesopotamia, about 825. This in turn was followed, after another long lapse of eight centuries extending through the Middle Ages, by several measures executed by different nations. The principle of triangulation which is used in the refined modern measures of distances was introduced in 1617.

Modern geodesy, as it now exists, began with the discovery of the law of gravitation by Newton, late in the seventeenth century, when he proved that the earth, as a revolving and not wholly rigid body, subject to its own attraction, must take the form of a slightly flattened sphere.

The form thus indicated by theory was apparently contradicted by the measure of an arc in France between 1683 and 1716, which indicated the earth to be an elongated sphere. To settle the matter, two memorable expeditions were sent out—one to the equatorial region of Peru (1735–1741) and the other to the polar region of Lapland (1736–1737). Their work proved Newton's theory to be correct, since they found the length of one degree to be greater, or in other words, the arc flatter, near the pole than near the equator. Since then, in theory and in practice, geodesy has advanced on sure ground and with ever-increasing precision in its results.

Though the early measures of the earth's curvature were made along meridians only, the modern methods of measures and computations are such that all the triangulation in a connected network may be utilized in the determination of the size and shape of the earth.

The same instruments and methods of observing are employed in a triangulation designed primarily as a basis for accurate map making as are used in measuring an arc for the purpose of determining the earth's size and shape. Nearly all geodetic arcs have been obtained incidentally during the progress of extended national surveys.

Since the revival and spread of science many surveys of countries, made primarily for mapping purposes and yielding, incidentally, geodetic arcs, have been carried out in different parts of the world. In making these measures France, Great Britain, Germany, Russia, and the United States have taken leading parts. Among the more recent measures there may be mentioned the Anglo-French arc, extending from the northern part of the British Isles southward into Africa; the great Russian arc, extending from the Arctic Ocean to the northern boundary of Turkey; the great Indian arc, extending from the southern point of India to the Himalayas; the European arc of a parallel, extending from southern Ireland eastward to central Russia. In the United States we have the transcontinental arc, extending along the thirty-ninth parallel from the Atlantic to the Pacific Oceans; the eastern oblique arc, extending parallel to the Atlantic coast from Maine to Louisiana; the ninety-eighth meridian arc, extending from Canada along the ninety-eighth meridian to Mexico, and thence through Mexico to the Pacific Ocean; the western arc, extending from Canada to Mexico along the Pacific coast; the Texas-California arc, extending from central Texas to the Pacific coast; the one hundred and fourth meridian arc, extending from central Colorado northward to Canada; the Utah-Oregon arc, extending from northern Utah, northwestward to Oregon, and thence down the Columbia River to the vicinity of Portland; the Alabama-Oklahoma arc, extending from Huntsville, Ala., westward through Memphis and Little Rock; the Texas-Louisiana arc, extending from the vicinity of Waco, Tex., eastward to the Mississippi River; the Rio Grande arc, extending along the Rio Grande from the Gulf of Mexico to a connection with the Texas-California arc; and the Great Lakes arc. The total length of the arcs of primary triangulation in the United

States is about 14,000 miles, more than one-half of the circumference of the earth.

The form of earth as given by the modern precise measurements is found to be such that with considerable exactness any section of it parallel to the Equator is a circle, and any section passing through both poles is an ellipse. The dimensions and form of this spheroid, or ellipsoid of revolution, as it may be called more accurately, are usually stated by giving its equatorial and polar radii or semidiameters. The most notable computations of the dimensions of the ellipsoid are those made by Bessel in 1841, by Clarke in 1866, and by the Survey in 1909. Bessel's and Clarke's values were derived from a combination of all the arc measures in different parts of the world. The Coast and Geodetic Survey value depends only on the triangulation done in the United States, but, on account of the application of the theory of isostasy, as explained below, the dimensions deduced by Hayford, of the Coast and Geodetic Survey, are considered the most accurate.

The Clarke ellipsoid has been used in the United States for many years for surveying and geographic purposes, and is the basis for all the charts of this Survey and for the maps of many other Government organizations. The Clarke ellipsoid is sufficiently accurate to be retained for those purposes. Its retention is especially desirable in order to avoid the immense amount of computation which would be involved in the adoption of a new ellipsoid of reference.

The dimensions of the earth as given by these different computations are as follows:

	Bessel (meters).	Clarke (meters).	Hayford (meters).	Hayford (English statute miles).[1]
Equatorial radius a	6,377,397	6,378,206	6,378,388	3,963.3
Semipolar axis b	6,356,079	6,356,584	6,356,909	3,950.0
Difference $a-b$	21,318	21,622	21,479	13.35
Compression $\frac{a-b}{a}$	$\frac{1}{299.2}$	$\frac{1}{295.0}$	$\frac{1}{297.0}$	

[1] 1 statute mile=5,280 feet, 1,609.347 meters.

Hayford took into consideration the theory of isostasy when making his determinations of the shape and size of the earth. The theory of isostasy postulates that at and beneath a certain depth below sea level, found by investigation to be about 122 kilometers (76 miles), the earth's materials are in equilibrium as if they were fluid. Therefore, in each column of the same cross section which extends from the depth of compensation to the actual surface of the earth, whether land or water, there will be the same mass or amount of material. In other words, the materials in any column would weigh as much as the materials in any other column, if the weighing were done at the same place. (See Gravity.) It is, therefore, assumed that elevated regions are

held up owing to the lesser density of the materials composing the columns of which they form parts and conversely the depression of the ocean bottoms is due to an excess of density in the material under them.

The above paragraph states what the condition would be with perfect isostasy. It is, of course, impossible to have complete isostatic adjustment in the earth's material because of some rigidity and viscosity but the investigations of the Coast and Geodetic Survey furnish conclusive proof that the isostatic condition in the United States approaches very closely to the ideal one.

The shape of the earth, but not its dimensions, has been determined by the Coast and Geodetic Survey in recent years from observations of the intensity of gravity. In 1912 the flattening of the earth or its compression was determined from 114 gravity stations in the United States. The value of the flattening was found to be 1/298.4. In 1916 a second determination of the flattening of the earth was made which gave a value of 1/297.4. In this determination there were used 348 gravity stations in the United States, Canada, several countries of Europe, and India. It is believed that the accuracy of this value 1/297.4 for the flattening or compression of the earth is the most reliable one in existence.

In the determination of this value of the flattening, the gravity stations were reduced for the effect of the elevation of the station above sea level, the attraction of the earth's mass above sea level, and the deficiency of the density in the ocean basins. There was also taken into account the attractive effect of the deficiency of the matter under the continents and the excess of material under the oceans. In other words, isostasy was considered in making the reductions.

To appreciate correctly the small amount of flattening at the poles indicated by the above figures, it should be noted that if a globe approximately 5 feet in diameter were constructed to scale to represent the earth, its equatorial diameter would be but one-fifth of an inch longer than its polar diameter. To the eye unaided by the use of calipers or other measuring instruments this globe would appear to be a perfect sphere.

The following brief statement gives some of the most important facts in regard to one of the arcs already completed in the United States and for which the final reports have appeared. This arc crosses the country along the thirty-ninth parallel from Cape May, N. J., to Point Arena, Calif., and is 2,625 statute miles (4,225 kilometers) long. The 10 base lines in this triangulation have an aggregate length of 53½ miles, one of them being nearly 11 miles in length. Many of the triangle sides in the Rocky Mountain region are over 100 miles long, and there is one line 183 miles, over which observations were made in both directions. Some of the triangulation stations were more than 14,000 feet (4,300 meters) above the sea. Many astronomic observations were

necessary to fix the position of this arc upon the earth and to determine the true direction of the lines of the triangulation. The latitude was determined accurately at 109 stations, the longitude at 29, and the azimuth or true direction at 73.

A powerful stimulus to progress in geodesy was given many years ago by the formation of a Geodetic Association in Europe, which was founded in 1861 and was made international in character in 1886. The United States became a member of this association in 1889. Previous to the Great War nearly all the progressive nations were members of the association. General meetings were held at least once in three years at which geodetic problems were discussed and reports were made in regard to geodetic operations of the various countries.

In July, 1919, there was organized at Brussels, Belgium, by a number of the nations which had been at war with the Central Powers what is called the International Research Council. Under this Council have been created several unions, one of them being the International Geodetic and Geophysical Union. One of the sections of this union deals with the subject of geodesy and it will probably take over all of the functions of the old International Geodetic Association.

See also the following publications of the U. S. Coast and Geodetic Survey: Figure of the Earth and Isostasy from Measurements in the United States; supplement to that report; Special Publications Nos. 10 and 12, each of which is entitled, Effect of Topography and Isostatic Compensation on the Intensity of Gravity; and Special Publication No. 40, entitled, Investigations of Gravity and Isostasy.